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APPLICATION OF DIRECTED GLASS FIBER REINFORCED PLASTIC TO HELICOPTER TAIL ROTOR ASSEMBLY

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June 1968

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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KAMAN AIRCRAFT CORPORATION

BLOOMFIELD, CONNECTICUT

U S ARMY MATERIEL COMMAND

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APPLICATION OF DIRECTED GLASS FIBER REINFORCED PLASTIC TO HELICOPTER TAIL ROTOR ASSEMBLY

KAMAN AIRCRAFT REPORT NUMBER R-717

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SUMMARY

An engineering program has been conducted for the purpose of investigating the feasibility of a new rotor concept utilizing a monolithic spar of directed glass fibers supported in an epoxy matrix. This concept makes use of the anisotropic property of the material to eliminate pitch bearings and thereby reduce maintenance requirements. The program included design, fabrication development, analysis and test phases. The latter two phases were of limited scope since the intent of the program was a basic feasibility investigation. The rotor has satisfactorily completed all phases including a 25-hour whirl test. It was concluded that rotors of this general configuration are practical, offer significant advantages, and can be fabricated in a production environment.

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INTRODUCTION

At the present level of development of the helicopter, many of the basic problems encountered in design have been satisfactorily solved and the engineering approach to these problems is well known. However, there remain significant areas in helicopter design where the techniques are still developing and where the results achieved are not always satisfactory. This is particularly true when new dynamic components must be designed to meet requirements of low maintenance and long life. An outstanding example of this may be found in the service history of tail rotors, which, due to their high rotational speed and adverse relative airflow, have regularly required high maintenance and frequent replacement. The introduction of new configurations, advanced metallurgy, and improved lubrication has made some improvement, generally at the expense of additional cost and weight.

The present report describes an initial evaluation of the feasibility of a basically new tail rotor concept utilizing directed glass fibers in a resin matrix to achieve a monolithic spar with the desirable strength and stiffness characteristics. This concept also seeks to exploit the natural anisotropic properties of the material through the accommodation of pitch change motion by virtue of elastic torsional deformations. Troublesome pitch bearings, with their attendant seals, oversize nuts, etc., are thereby eliminated. Further, the design contemplated a two-bladed teetering rotor suitable for application to the UH-1. This permitted an arrangement in which the primary structural fibers of the spar are continuous from blade tip to blade tip. Such a design has no primary structural joints or connections in the main load-carrying member and thereby eliminates one of the main sources of stress concentration and failure.

Details of the design, analysis, fabrication development, and initial testing, including 25 hours of whirl testing of this unique tail rotor, are presented in this report. Since it was apparent from the outset that this rotor concept would require the development of advanced fabrication techniques, the major emphasis of this initial program was in that area, with only sufficient analysis and testing to demonstrate that a potentially useful article was being developed. An overall view of the rotor is shown in Figure 1.

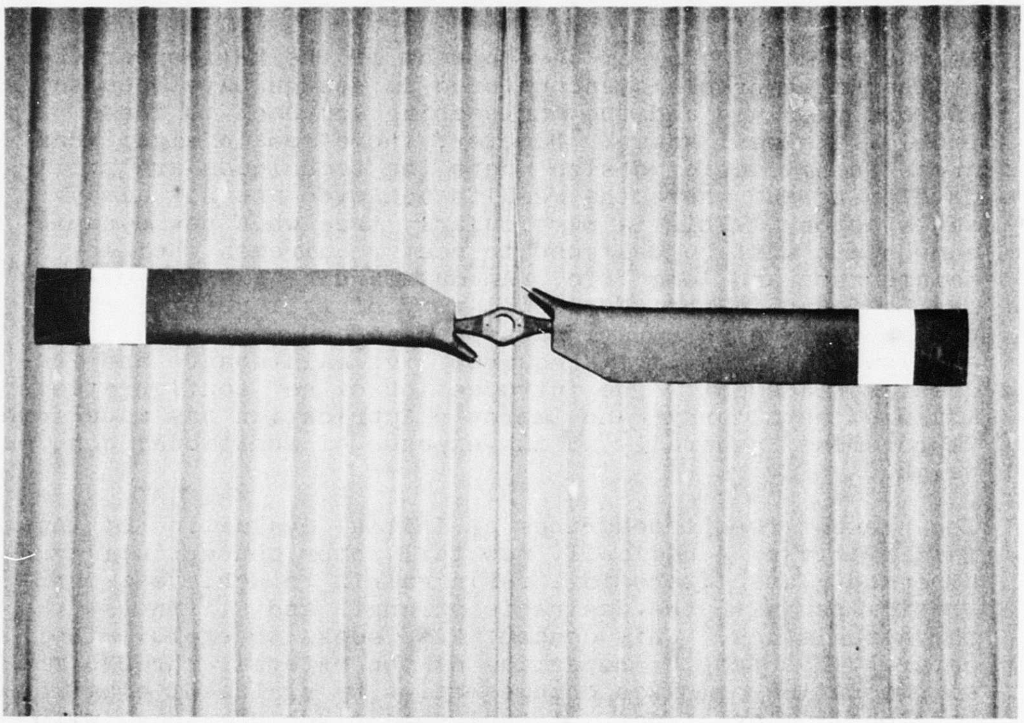


Figure 1. Complete Fiber Glass Tail Rotor Less Mounting Components.

DESIGN APPROACH

The basic problem undertaken in this program was the design of a fiber glass reinforced plastic tail rotor which takes maximum advantage of the properties of the material and which is compatible with the geometry and installation of a selected demonstration vehicle, the UH-1 helicopter. In addition to the inherent properties of the material, low weight and freedom from corrosion, it was desired to take advantage of the anisotropy of the directed fibers and to incorporate a torsionally flexible spar segment which would permit the elimination of highly loaded pitch bearings. A further advantage could be gained through the elimination of structural joints and connections by continuing all primary spar fibers through the hub area and making them an integral part of the opposing airfoil sections.

The basic fabrication process would then consist of a preliminary lay-up of a full-length spar (blade tip to blade tip) incorporating a finished hub area, a secondary step in which prefinished airfoil panels are attached to the spar, and a final step in which pitch horns, root end cuffs, and tip caps are added. The spar material which is continuous for the full length of the rotor has vastly different duties to perform in the various sections of the rotor. Near the tip of the blade, it is lightly loaded and provides the attachment of the airfoil shells to the inboard areas. Inboard of the basic airfoil, the spar forms the pitch-spring region which transmits the full blade centrifugal force and bending loads while permitting torsional deflections to accommodate blade pitch. At the inboard termination of this section, the spar undergoes transition to the hub area, where the basic load-carrying fibers surround the shaft and react blade centrifugal force from blade to blade.

It is apparent, then, that this tail rotor design may be viewed in terms of sections or structural areas, each of which has special problems of loading, deformation, and fabrication procedure. These will be examined individually in what follows; however, because of the importance of the pitch-spring concept and the high loading that this section must endure, it will be discussed first.

PITCH-SPRING AREA

The pitch-spring area is defined as that portion of the spar between blade stations 6.0 and 18.0 approximately. Within this length, the spar must be of a relatively confined constant cross section in order that blade pitch variations may be accommodated with the application of modest torsional moments which produce low torsional strains. A section with smooth external contours having no reentrant corners will have the most uniform distribution of torsional strains. At the same time, this section must be capable of reacting blade centrifugal force and bending moments in both the flatwise and edgewise directions. Since the stiffness requirements for a rotor are greater in the edgewise or in-plane direction than in the flatwise direction, it is logical that the section should have the material disposed in such a way as to yield this result. Another consideration which influenced the choice of spar cross section was the desire for accuracy and repeatability in both external surface dimensions and in spar stiffness. Various means for accomplishing this were considered; however, after some study, the one chosen was a fabrication technique which involved the use of a rigid female mold and internal pressurization of a hollow cross section. Pressure application was necessarily of a fluid nature and required the use of internal bags capable of compensating for dimensional changes during cure. This approach eliminated any need for final machining or sanding operations which would have the effect of severing or damaging surface fibers which are important in bending.

Taking into account all of the above considerations and the general desire to maximize any necessary radii of curvature, the natural result for the cross section of the pitch-spring area is a thick-walled ellipse having an aspect ratio of approximately 2.0. The major axis of the ellipse is oriented in the chord plane, thus giving the desired stiffness relation.

The major axis of the ellipse which defines the outside spar contour is 1.25 inches, while the inner axis is 0.625 inch. The wall thickness of the section varies from 0.17 inch along the minor axis to 0.26 inch along the major axis. This wall thickness variation, as well as the desired structural properties of the section, is achieved by judicious location and orientation of the various plies of the basic structural material, unidirectional glass fibers in an epoxy matrix. This material and the reasons for its selection are discussed more fully in the section of this report dealing

with process development. However, the main reason for its selection is its highly anisotropic properties, particularly the fact that it has high strength and stiffness when loaded parallel to the direction of the glass filaments and much lower strength and stiffness at other load orientations, diminishing to a minimum for loads applied perpendicular to the filament axis.

In the pitch-spring area of this rotor, the primary loadings are centrifugal force and bending, all of which produce maximum principal stresses in the spanwise direction. This in turn dictates that the majority of the structural material shall have its high-strength axis aligned in the span direction. A sufficient number of filaments must be oriented in the chord direction to support the epoxy matrix in reacting the modest stresses that are so oriented. However, no plies are incorporated with intermediate orientation since it is desired that this section have low torsional stiffness. The proper mixture of spanwise and chordwise material was determined empirically in the development phases of the work.

HUB AREA

The configuration of the hub area of this rotor is dictated by several considerations. To maintain the advantage of having no structural joints in the main load-carrying elements by having continuous fibers from blade tip to blade tip, it is necessary that these fibers bypass the rotor shaft and its coaxial control rod. It is therefore required that a transition take place in which the spar material of the pitch-spring area be divided into equal segments to pass on either side of the rotor shaft. Since the chosen method of fabrication involves internal pressure and closed female mold, the cross section in the hub area becomes a bifurcated hollow which is strengthened and stiffened locally by the addition of interleaved cross plies. Filament directions for these plies are regularly varied so that optimum utilization is achieved.

The hub area is also characterized by the inclusion of an aluminum insert which supports the load-carrying fibers and maintains their correct position for the excursion through the hub area. This insert is bored to accept the rotor shaft and also contains provisions for attaching the rotor mounting hardware. At each end of the insert where the transition from the bifurcated section to the elliptical pitch-spring section occurs, there exists a tendency for spanwise splitting. This arises from the change in direction of the span-

wise load-carrying fibers and the natural desire for them to assume a straight, direct load path from point of application to point of load reaction. Splitting of this nature was overcome by the incorporation of an external filament winding which completely covers this transition region. The direction of the filaments is circumferential, and the necessary strength is supplied by hoop tension in the filaments. This external reinforcement, in addition to interleaved cross plies of various orientation, provides a light, efficient means for resisting a local concentration of strain which could not be provided in metal fittings without the introduction of secondary stress concentrations and other severe design compromises.

In the development of the fabrication techniques for this rotor, considerable attention was devoted to the hub area and in particular to the quality of the primary structural filaments in this area. Early attempts yielded a structure containing filaments which deviated significantly from the desired smooth transition; in fact, some contained sharp kinks incapable of transmitting the proper loads. This problem was eventually overcome by the adoption of a fabrication technique which involves pretensioning of each individual ply or tape. This procedure is discussed more fully in the subsequent section on process development. The investigation and introduction of this technique were significant accomplishments of this program.

BLADE AIRFOIL PANEL

This area of the rotor was investigated from a design point of view in some depth. The relation of the spar to the airfoil shell, the length of the spar pitch-spring section, and the attachment of the pitch horn were among the design considerations involved. The early concepts involved a transition of the spar cross section from the ellipse of the pitch-spring area to a "D-spar" in the airfoil section. The "D" formed the forward portion of the airfoil, and the aft portion was made up of a honeycomb core with fiber glass skins. The pitch horn joined the spar near the transition area and reached inboard to provide a control connection on the teeter axis. Since the length of the pitch-spring section of the spar was approximately 12 inches in order that torsional strains would be kept within acceptable limits, a pitch horn of exceptional length was required. The resulting apparent softness of the pitch control system and the effects of spar bending deflections on rotor stability and control were questions that would require detailed investigation with this configuration.

The design which was finally selected involved the use of a spar whose section remained essentially constant through the pitch-spring area and the full length of the airfoil to the blade tip. To the elliptical spar are added airfoil shells which are prefinished in halves. Each half represents either the upper or the lower portion of the symmetrical airfoil as divided by the chord plane and is made up of an outer skin of fiber glass, an inner skin or facing of fiber glass along the chord plane which closely matches the spar contour locally, and a carved aluminum honeycomb core which maintains the airfoil shape. These shells bond firmly to a heavy former at station 18 and to the spar itself from there to the tip of the blade. They also incorporate an integral inboard extension or cuff which surrounds but does not contact the spar from stations 18 to 6, the pitch-spring segment. At station 6, the cuff is connected to the spar through an elastomeric support. This support follows the technology developed for elastomeric bearings, in that it makes use of thin laminations of steel and rubber in a cylindrical assembly for the purpose of permitting relatively large amplitudes of relative rotation while maintaining high radial stiffness. In this application, the elastomeric support acts primarily as a steady-rest to react shear loads induced by the controls. The blade pitch horn extends forward from the inboard end of the cuff and provides a short, stiff connection to the controls at a point collinear with the hub teeter axis. Input loads from the control system are reacted by the elastomeric support, and the residual torsional moment is transmitted by the cuff to the heavy rib at station 18. This moment provides the elastic torsional deformation of the pitch-spring segment of the spar and hence the desired blade pitch change.

The blade airfoil panel also contains a leading edge mass balance weight and a tip cap. The mass balance weight is basically a half round steel rod which is nested inside a nose cap. The weight is bonded to a precured nose cap as a subassembly, and this is then bonded over the leading edge of the two airfoil shells. The inboard end of the weight contains provisions for the attachment of a fail-safe bulkhead which could carry the centrifugal load should the bond become completely severed. At the tip of the weight, there are provisions for attaching balance weights for mass balance of the rotor assembly. The tip of the blade airfoil section is covered by a cap which is made up of two plies of preimpregnated number 120 fiber glass cloth fully cured and bonded to the blade.

PROCESS DEVELOPMENT

The major achievement of this program was the development of processing techniques which represent an advance of the state of the art of the materials technology for fiber glass reinforced plastics. The laboratory program which developed these techniques and the simulated production program which evaluated their application are discussed in this section. The program began with a materials evaluation and selection phase. This phase concentrated on the choice of materials for the spar which had the unique requirements of high tensile strength in the spanwise direction and low torsional stiffness. These requirements can be met by the application of unidirectional glass fibers in an epoxy matrix. This material is available commercially in several forms. Once the selection had been made and verified, the task became one of applying this material to the particular design problem at hand: a helicopter tail rotor with continuous glass fibers from blade tip to blade tip.

MATERIALS SELECTION

A survey of available materials was conducted making use of vendors' literature and other published data. To be sure that all available materials were considered, direct contact with each of the manufacturers in the field was established. Since the laboratory had considerable experience and background in reinforced plastics, and in particular with unidirectional glass fibers supported in an epoxy matrix, the materials evaluation and selection job was greatly simplified.

The complexity of the lay-up for the tail rotor spar with its hub area transition and section changes dictated the use of a preimpregnated, high-strength, unidirectional material with improved strength in the cross direction and improved handling and comformability. The product originally selected as meeting these requirements was a reinforced plastic designated type XP-206. This material consisted largely of unidirectional glass fibers embedded in a matrix of epoxy resin which is qualified under MIL-R-9300A. An important feature of this material is that the tape or roll supplied from the manufacturer contains a thin support cloth or leno weave of fiber glass which contributes greatly to the handling characteristics. It has a cured thickness per ply of .011 inch and a resin content of 36 percent. The shelf

life is 6 months, and the material cures at 325°F. It is capable of achieving a unidirectional tensile strength of 140,000 psi and a tensile modulus of 6.7 x 10^6 psi.

The XP-206 material was used to fabricate several of the early spars; however, this was an experimental material and was later dropped by the manufacturer. This forced a change to a similar material, type 1008S, manufactured by the same supplier. Thickness and cure cycle were essentially identical; however, the resin content was 38 percent. This material has the capability of achieving a unidirectional tensile strength of 165,000 psi and a tensile modulus of 6.0 x 10^6 psi.

Both of these materials were evaluated for the specific application of the spar for this tail rotor. For this purpose, it was considered appropriate to use thickness and lay-ups simulating the spar wall. Also, an investigation of the effect of cure cycle on physical properties seemed in order, as a lengthy post-cure was recommended which could strongly influence manufacturing costs. The details of the evaluation and the results follow.

Type XP-206

Seven panels were fabricated using various lay-up and cure procedures. Panels 1 through 3 consisted of 13 plies of unidirectional XP-206. Panels 4 and 5 consisted of 12 plies of unidirectional XP-206. Panels 6 and 7 consisted of 13 and 14 plies of XP-206 respectively. In panel 6, the first and seventh plies were cross plies and the second through sixth and eighth through eleventh were spanwise. The twelfth and thirteenth plies were oriented +5°-5° intersecting one another. In panel 7, the first and eighth plies were cross plies and the second through seventh and ninth through twelfth plies were spanwise. The thirteenth and fourteenth plies were oriented at +5°-5° crossing one another. Panels 6 and 7 were fabricated to simulate spar fiber orientation.

The actual buildup of the panels took place in a mold with internal dimensions of .125 in. x 10½ in. x 10½ in. Prior to the buildup of the laminates, the mold was cleaned and sprayed inside and out with a fluorocarbon mold release. After the mold release was allowed to air dry for 15 minutes, the plies were positioned in the mold cavity, one at a time, with the glass filaments oriented as required. No overlap of the plies on the edges of the mold was allowed. Plies were

rolled flat as they were positioned in the mold. On completion of the buildup, a layer of mold release paper was positioned on top and was covered by a thick (10½ in. x 10½ in.) aluminum plate.

Panel 1 was positioned in a Wabash press at room temperature with a rubber diaphragm air pressure vessel attached to the upper platen. On closing the press, the air bag was pressurized to 50 psi and press set for 330°F. On reaching 330°F, the laminates were cured for 1 hour at 330°F at 50 psi. Panel 2 was cured in the same fashion.

Panels 3 through 7 were built up in the mold similar to panel 1. The buildup and mold assembly were vacuum bagged. Vacuum was maintained throughout cure of the laminate. The assembly was positioned in the Wabash press preheated to 180°F. The press was closed, exerting contact pressure only, and the assembly was heated approximately ½ hour at 180°F. On completion of the preheat cycle, pressure was applied to bring the press down to .125 inch stop. At this point the press was opened and the rubber diaphragm air bag was positioned on the buildup. The press was closed, the air bag was energized to 50 psi, and the press was set for 330°F. On reaching 330°F, the laminates were cured for 1 hour at 330°F and 50 psi. On completion of cure, the laminates were post-cured for 16 hours at 280°F except as noted in the test data.

On completion of the prescribed cure cycle, the laminated panels were made into tensile, flexural, and interlaminar shear specimens. Aluminum tabs were bonded to the grip ends of the tensile specimens using MIL-A-5090 Type I epoxy adhesive for bonding the aluminum to laminate. The interlaminar shear samples were taken from the center and edges of the panel. All specimens were tested in accordance to Federal Test Standards 406, 1031, 1011, and 1042.

The rubber diaphragm attached to an air pressure vessel had been selected to cure all of the test panels because it simulates the fluid pressure system proposed in the cure of the tail rotor blade. The fluid pressure system insures uniform pressure on all portions of the laminate throughout cure.

A review of resin content of the various panels fabricated and tested shows a variation from 27.2 percent to 35.5 percent. No appreciable difference in mechanical properties was evident (see Table I). Post-curing of the laminates resulted in a slight improvement in mechanical properties. A difference in ultimate tensile strength was observed between specimens with

¼ inch-wide flat sections compared to those with 1/8-inch-wide sections. The test results of the ¼-inch-wide specimens were more consistent. Increasing the post-cure temperature from 280°F to 320°F and curing the laminate for 16 hours improved the interlaminar shear properties of the laminates but adversely affected the flexural strength, as revealed by the test results of specimens 3 and 7. Interlaminar shear values remained fairly consistent but slightly lower than stated in the manufacturer's literature for all panels checked, with the exception of panels 5 and 7.

The variation in the thickness of panels 1 and 2 necessitated a change of the curing procedure for the remaining panels. A preheat cycle was added, and the laminate was pressed to stops in a hard platen press at the end of the preheat cycle. This change brought about better control of panel thickness. The tensile and flexural test data for panels 1 and 2 were adjusted to a common base to minimize the thickness variable.

Evaluation of Results

The evaluation of XP-206 has shown the consistent mechanical properties of the glass fiber pre-preg. XP-206 meets the mechanical requirements of MIL-P-25421-A but has not been qualified to this specification. However, the resin system is Type 1002 epoxy resin which is approved to MIL-R-9300. The selection of XP-206 over 1002 was based on the elimination of fiber distortion during layup of the laminate, better handling characteristics, and a slight improvement in strength in the cross-ply direction. The difference between XP-206 and 1002 is that a leno-weave ply approximately .002 inch thick was added to unidirectional pre-preg.

Variation in resin content of approximately 8 percent and a post-cure cycle of 16 hours at 280°F had little effect on increasing the mechanical properties. It is felt that the initial cure of 1 hour at 320°F $\pm$10°F instead of 10 to 20 minutes at 325°F has brought about a high percentage of cross linking not obtainable in the shorter cure cycle and has consequently eliminated the need for a long post-cure.

The post-cure of panels 5 and 7 at 320°F for 16 hours has optimized the interlaminar shear properties but has also reduced the ultimate flexural property. An optimized resin system represents a compromise of properties to accommodate a particular design.

TABLE I. EVALUATION OF THE MECHANICAL PROPERTIES OF XP-206 UNIDIRECTIONAL GLASS FIBER EPOXY PRE-PREG

Panel No.	Description	Thickness (inches)	Resin Content (%)	Ult. Tensile (psi)	Mod. (psi x 10^6)	Ult. Flexure	Mod. (psi x 10^6)	Inter-laminar Shear (psi)
1	XP-206; 13-ply, unidirectional; no post-cure	.126 avg	27.2	143,000*#	5.75	147,400*	4.72*	3604
2	XP-206; 13-ply, unidirectional; no post-cure	.128 avg	35.5	159,320*	5.38	150,300*	5.18*	3276
3	XP-206; 13-ply unidirectional. Post-cured 16 hours at 280°F.	.126 avg	29.3	167,000	5.71	153,000	5.10	3496
4	XP-206; 12-ply unidirectional. Post-cured 16 hours at 280°F.	.126 avg	31.5	154,724	5.13	151,040	4.82	3784
5	XP-206; 12-ply unidirectional. Post-cured 16 hours at 320°F.	.126 avg	33.9	158,000	5.50	137,200	4.96	4312
6	XP-206; 13-ply simulating spar build-up. 1st & 7th ply, cross ply; 2nd through 6th & 8th through 11th, span-wise; 12th & 13th, $\pm 5°$. No post-cure.	.124 avg	31.3	116,660	4.96	128,800	4.28	3086

* Data adjusted to common thickness.

\# The flat section of the tensile specimens of panel 1 was 1/8 inch wide. The tensile specimen of all other panels had 1/4-inch-wide flat sections. All numerical values are an average of five measurements.

TABLE I - Continued

Panel No.	Description	Thickness (inches)	Resin Content (%)	Ult. Tensile (psi)	Mod. (psi x 10^6)	Ult. Flexure	Mod. (psi x 10^6)	Inter-laminar Shear (psi)
7	XP-206; 14-ply simulating spar build-up. 1st & 8th cross ply, 2nd through 7th & 9th through 12th spanwise, 13th & 14th $\pm 5^o$. Post-cured 16 hours at 320^oF.	.137 avg	29.3	128,500	5.06	139,800	4.68	4328

* Data adjusted to common thickness.

\# The flat section of the tensile specimens of panel 1 was 1/8 inch wide. The tensile specimen of all other panels had 1/4-inch-wide flat sections. All numerical values are an average of five measurements.

Note: Specification Requirements MIL-P-25421 Unidirectional

Ult. Tensile Strength	100,000 psi
Ult. Flexure	125,000 psi
Flexural Modulus	5.0×10^6 psi

Type 1008S

Panel fabrication and cure procedures were identical to those of the initial evaluation of XP-206.

Five panels numbered in continuing sequence were fabricated and tested. Four of these panels were made of 1008S, and the remaining panel was XP-206. Three test panels of 1008S were initially fabricated and tested, followed by one panel each of XP-206 and 1008S which were processed and tested together for a direct comparison of mechanical properties. Panels 8 through 10 were compared to panel 7.

Results of testing are tabulated on Table II.

Resin content was varied slightly by increasing the thickness of the mold stops from .125 inch to .143 inch. The thickest panels had the highest resin content and lowest ultimate tensile values.

Panel 8 had the lowest interlaminar shear values. This was the first panel tested of this series. A review of testing procedure revealed that a considerable amount of peel occurred at the shear joint during testing as a result of insufficient clamping pressure on the backup plates. This was corrected for all subsequent panels.

A variation of ultimate flexure strength of approximately 12 percent was observed when alternating the cross-ply surfaces of the specimen from the compression side to tensile side of the test fixture prior to testing.

The mechanical properties of 1008S are comparable to those of XP-206. Variation of resin content from 28 percent to 33 percent had little effect on the mechanical properties of the laminates with the exception of a reduction in ultimate tensile by 10 percent.

The interlaminar average shear value for panels 9 through 12 is lower than the average of the previous group tested. The difference is caused by test variables.

1008S is considered to be acceptable for this application, considering both its fabrication and its structural characteristics.

TABLE II. EVALUATION OF THE MECHANICAL PROPERTIES OF XP-206 AND 1008S UNIDIRECTIONAL GLASS FIBER EPOXY PRE-PREG

Panel No.	Description	Thickness (inches)	Resin Content (%)	Ult. Tensile (psi)	Mod. (psi x 10^6)	Ult. Flexure	Mod. (psi x 10^6)	Inter-laminar Shear (psi)
8	1008S 14-ply simulating spar buildup. 1st & 9th cross ply, 2nd through 8th & 10th through 14th span-wise. Post-cured 16 hours at 280°F.	.134 avg	28.9	141,600	5.44	148,720	4.44	2336*
9	Panel identical to panel 8	.137 avg	30.4	133,240	5.05	147,780	4.52	2919
10	Panel identical to panel 8	.137 avg	30.7	131,920	5.42	138,720	4.56	2844
11	Panel identical to panel 8	.1416 avg	31.0	126,360	5.55	143,000	4.80	3736
12	Lay-up of panel identical to panel 8. Material of the panel XP-206.	.143 avg	33.0	127,040	5.06	135,880	4.69	3466

* Improper clamping of specimen resulted in peeling of joint.
All numerical values are an average of five measurements.

SPAR FABRICATION

The spar fabrication development process was one of evolution. It began from the basic concept of curing preimpregnated material in a rigid female mold under the application of fluid internal pressure. This approach offered the greatest possibility for uniformity of the end product in terms of external geometry, resin content, and physical properties of the material and of the assembly. To achieve these goals in the relatively complex spar/hub component required the design and development of tooling which would permit a step-by-step lay-up procedure preparatory to a controlled cure of the assembly. The development of both the tooling and the process was approached by investigating the techniques and problems on subscale samples and then proceeding to full-scale and to full-length components.

The following is a chronological report of the approach, the evaluation, and the conclusions for each spar in the order of spar fabrication. It is considered important to include the details of each, as a full appreciation of the problem can be gained only when the total experience of success and failure for each processing variation attempted has been digested. It will be noted that each successive trial made use of information developed on previous samples in order that improvements could be incorporated and apparent deficiencies corrected.

Spar 1

This spar was approximately a half-scale mock-up which simulated the lay-up technique and the relation of the aluminum hub insert to the fiber glass structure in the hub area. This specimen verified some of the basic assumptions concerning lay-up procedures and tackiness of the material. As a result of this study, the basic mold configuration was established as a four-piece design with top, bottom, and two side plates.

Spar 2

The hub and torsion specimen consisted of XP-206 unidirectional glass fiber epoxy pre-preg buildup on an aluminum hub. The torsion area spar wall consisted of 16 plies of a unidirectional epoxy pre-preg XP-206. The inner and ninth plies were cross plies, the outer plies (thirteenth and nineteenth) were 5 degrees orientated and crossed one another, and the remaining plies were parallel to the spanwise axis. The hub area is composed of an aluminum insert to which the

pre-preg strips are bonded. The outer spar wall consisted of 19 plies: 14 spanwise plies and 5 cross plies. The inner spar wall consists of 9 plies: 5 cross plies and 4 spanwise plies. Prior to assembly, the aluminum hub was cleaned, etched, and primed with EC-1682 primer. Thickness of the primer coat was .0005 inch to .001 inch.

The hub buildup consisted of wrapping the primed groove, in the perimeter of the aluminum hub, with 5 cross plies and 4 spanwise plies sandwiched between the cross plies, with a cross ply in contact with the hub. On completion of the hub buildup, phenolic plugs were positioned at the midpoint of the groove in the grip assembly and heat tacked in place as shown in Figure 2. The "Y" shaped pressure bags were positioned into the grooves, with the bag ends butting against the phenolic plugs. The opposite ends of the bags were taped to the end posts of the spar assembly fixture. The outer cross plies in contact with the pressure bags in the hub region were wrapped tightly over the pressure bags and heat tacked in place. Torsion area cross plies were positioned so they butted the hub cross ply and were tightly wrapped around the pressure bags and heat tacked in place. The second through seventh and ninth through thirteenth were spanwise plies. Cross plies were positioned between every spanwise ply in the transition zones of the hub. The first and ninth plies were cross plies extending the full length of the specimen; the thirteenth and fourteenth plies were positioned at $\pm 5^{\circ}$ spanwise to the spar axis so the plies crossed one another.

The spar assembly was positioned in a female mold, and air fittings were attached to the pressure bag. The spar and the mold assembly were preheated in an oven for 1½ hours at 180°-200°F. On completion of the preheat cycle, the mold was immediately removed from the oven and closed. The upper hub plate was locked in place prior to securing the side hub plates.

The pressure bags were then pressurized to 75 psi, and the mold assembly was oven cured. The cure cycle was $325^{\circ} \pm 10^{\circ}$F at 75 psi for 1 hour. On completion of cure, the spar and the mold assembly were allowed to cool to 120°F, maintaining 75 psi pressure on the laminate. The hub torsion assembly was allowed to cool to room temperature prior to removing it from the mold.

Lay-up of the hub and torsion section of the spar had proceeded according to plan. Problems that were encountered are as follows:

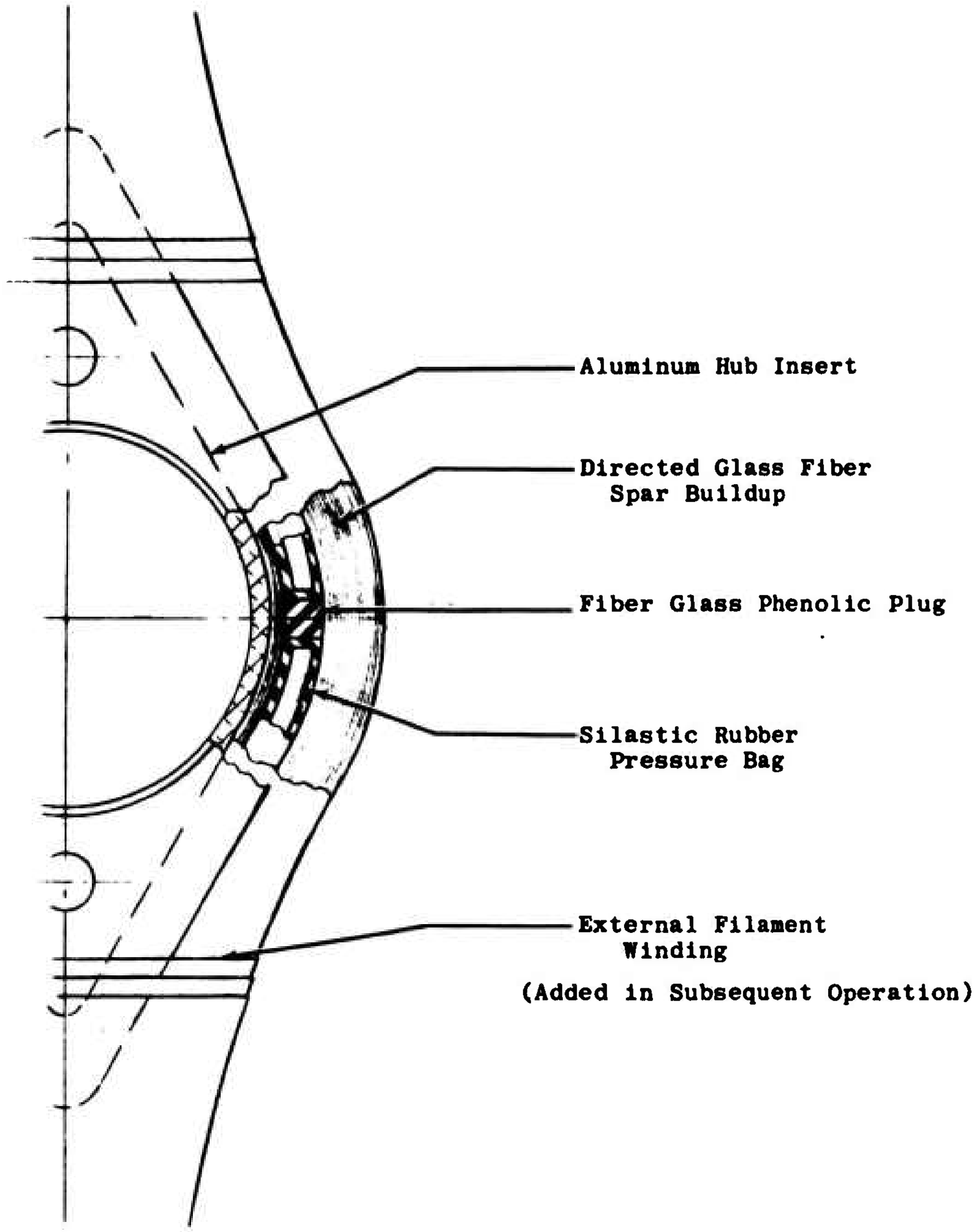


Figure 2. Sketch Showing Relative Position of Components at Time of Spar Cure.

1. The cross plies in the hub transition zone were too wide, making location and positioning on the buildup difficult.

2. Attaching the "Y" shaped pressure bags to the hub was not positive; during fabrication of the spar, they slipped outboard, allowing a large gap to develop between the hub and the buildup.

3. Positioning the 5-degree orientated spanwise plies could not be accomplished without cutting the spanwise plies in the hub region. Difficulty was experienced in maintaining the 5-degree angle throughout the length of the torsion sections.

4. The hub portion of the mold could not be closed.

Examination of the spar on the completion of cure showed the following:

1. Excessive flash in the hub transition zone; thickness in this area was approximately .090 inch over blueprint tolerances.

2. Mismatch between the hub and torsion spar mold sections.

3. Spanwise grooves approximately .030 inch to .060 inch wide and filled with cast resin occurred in the hub transition zone on the upper and lower surfaces.

Initial torque testing of the spar assembly produced spanwise cracks at the outboard tips of the aluminum grip. On testing the assembly to its ultimate tensile strength, these spanwise cracks propagated in a spanwise direction outboard until failure occurred in the hub region. Examination of the failed area revealed the following internal discrepancies in the buildup:

1. The cross plies were distorted and were nonsymmetrical.

2. Porous areas occurred in the laminate at the vertex of the spanwise plies in the hub region adjoining the extreme outer edge of the aluminum grips.

The static tensile test of spar 2 resulted in failure in the hub transition zone at station 3.25 in a section of low fiber density having a considerable amount of porosity. The failure of the specimen originated at the extreme outboard edges of the aluminum grip and propagated outboard in a spanwise direction until reaching a porous area where the majority of the spanwise through-fibers were ruptured. The failure at station 0 trailing edge was secondary. The specimen failure was the result of porosity and distorted through spanwise plies in the transition hub zone.

The major fabrication problems occurred in the hub area. The hub buildup was too massive and prevented full closure of the hub portion of the mold. On the subsequent buildup, the width of the cross plies in the hub region will be reduced to half of this original width. A reference point, the outermost edges of the aluminum grip, will be used to position all of the cross plies in the hub buildup area. To prevent the outboard movement of the pressure bag from the hub during fabrication, a ply of unidirectional XP-206 pre-preg $\frac{1}{4}$-inch times 12 inches will be used to attach the bag to the hub grip buildup. The 5-degree orientated outer spanwise plies were eliminated due to the difficulty in maintaining ply orientation and the fact that they were not through spanwise plies due to hub configuration. The 5-degree orientated plies will be replaced with through spanwise plies.

Spar 3

Buildup for spar 3 was the same as that for spar 2 with the following exceptions:

1. The width of the cross plies in the hub transition zone was reduced to half of the original width, and all plies were located using the outboard edge of the grip as reference points.

2. The two 5-degree orientated plies were replaced with two spanwise plies of XP-206.

3. An outer ply of M-159 #120 epoxy pre-preg was added to the spar and grip areas during the fabrication of the spar.

A problem encountered in the lay-up of the spar was as follows:

The attachment of the "Y" shaped pressure bags to the hub buildup was not adequate. During the buildup of the spar, the pressure bags moved outboard, resulting in a loss of pressure in the transient region of the laminate during final cure.

During cure of the spar laminate, air leaks developed in the hub region of the spar, in the vicinity of the phenolic plugs. Difficulty was again experienced in closing the hub portion of the mold.

Examination of the completed spar on removal from the mold revealed the following surface defects:

1. Chordwise wrinkles occurred on the leading edge of the spar at station 2.70 at both ends of the hub. The depth of the depressions was approximately .060 inch.

2. Spanwise creases occurred in the transition area. The majority of these creases were filled with cast resin.

Mismatched spar sections occurred between the torsion area and transition zone; they were similar to, but not as severe as, those found with spar 2.

The spar specimen was intended for torsional stiffness checks; however, during the initial phase of testing, application of tensile load, the specimen yielded at 6000 pounds and failed in tension at 9000 pounds in the hub area.

On dissecting the spar after the tensile failure, the following internal discrepancies were found:

1. Porosity between the plies in the transition zone on both sides of the spar.

2. Irregularity of the inner spar wall and the collapsing of the material around the phenolic plug.

The tensile failure originated in the vicinity of the chordwise indentations on the leading edge. Spar 3 failed at a very low value in comparison to spar 2. Destructive examination and comparison of spar 3 to spar 2 revealed a greater number of crimped and distorted spanwise fibers and porosity in the hub region of spar 3, resulting in the lower ultimate tensile values. The main fabrication difficulty

encountered in the buildup of this spar was maintaining the pressure bag in the hub buildup. The bag continued to move outboard throughout the lay-up of the spar. The inner ply on the subsequent buildup will be premolded, with a circular cross section and slit in a spanwise direction on the upper surface. This will also facilitate the attachment of the pressure bag to the buildup and prevent collapsing of the inner spar wall in the phenolic plug region at station 0.5. Substituting a fully molded inner ply of 181 cloth for the present cross ply of XP-206 will insure a more uniform spar wall in the hub transition area, since the buildup can be laid up tighter on the preformed inner ply. A reduction of porosity in the hub transition area can also be expected.

The closing of the hub portion of the spar mold, upper hub plates, and side hub plates is causing serious distortion and mutilation of the through spanwise plies.

Spar 4

Buildup for the spar and hub assembly was similar to that for specimens 2 and 3 with the following exceptions:

1. The cross ply of XP-206 inner spar ply adjoining the pressure bag was replaced with a precured ply of Cordo M159 Number 181.

2. Curing pressure of the laminate was increased from 75 to 90 psi.

3. The primer of the grip was changed from EC-1682 to BR-1009-49, and a ply of FM-1000 .030 lb/sq. ft. density was heat tacked to the primed surfaces.

The preformed inner plies of the spar assembly were fabricated from Cordo's M-159 Number 181 fiber glass cloth epoxy pre-preg. The pre-preg was template cut and vacuum molded, forming the inner skin plies of the hub and torsion area.

Six strips, three per side, of FM-1000 1½ inches by 2 inches were laid into the aluminum hub grooves and heat tacked in place. The remainder of the hub buildup was identical to that of spar 2.

The spar assembly was positioned in the mold and preheated to 180°F for 30 minutes. On completion of the preheat cycle, the mold was removed from the oven and the hub section of the mold was closed following the sequence established on spar 2. The end fittings for the pressure bags were

installed, and the mold assembly was positioned in the oven and cured for 1 hour at 330^{o}F at 90 psi. On completion of cure, the laminate was removed from the oven and allowed to cool to room temperature, maintaining 50 psi pressure on the laminate.

The main problems encountered in fabrication and cure of the spar were as follows:

1. Maintaining tensile load on the through spanwise plies during fabrication.

2. Holding torsional buildup zone in place during mold closure.

Examination of the spar on completion of cure showed the following defects:

1. Chordwise wrinkles occurred on the leading edge of the spar and hub region at station 3.25 on both ends of the hub.

2. Porous areas adjoining the outboard tips of the aluminum grips, triangular in shape, occurred on the top and bottom surfaces.

The hub portion of the buildup is still the major problem area. The pressure bag again slipped away from the buildup during lay-up of the spar. On final cure of the spar laminate, a leak developed between the external air hose adapter to the pressure bag; this leak could not be corrected and resulted in low laminating pressure in the right-hand spar member.

On static testing of the spar, a low tensile failure occurred at station 3. The cause of the failure was the porosity and distorted fibers in the hub transition zone.

Radiographic examination of the spar prior to testing and dissection indicated areas of porosity in the hub transition area and other internal discrepancies which were verified on destructive examination.

Since the phenolic plug is unable to control and prevent the outboard movement of the pressure bag from the hub buildup during lay-up and the collapse of the spar wall adjoining the phenolic spacer plugs at station 0, it will be eliminated. A one-piece pressure bag extending through the spar

laminate from tip to tip will be fabricated and is planned to be used on all subsequent blades. Application of a controlled tensile load uniformly applied to the spanwise plies during or directly after the closing of the hub mold will straighten the spanwise fibers and eliminate the distortion that has occurred on all the spars built to date, on the closing of the hub portion of the mold.

On destructive examination of the spar assembly, a chordwise cut through the laminate to station 3.25 was made to view ply orientation. The hub cross plies in the transition were distorted and displaced. All subsequent molded spars will be filament wound for the entire length of the transition zones (station 2.125 to station 6.25) with eight wraps of SCG 1/2 3.8s HTS 901 fiber glass.

The amount of porosity and voids found on destructive examination in the hub transition regions of the spar indicates that the inner ply (a formed, partially cured pre-preg) is not transmitting uniform pressure to the spar laminate. This first preformed ply will be replaced with combined buildup of XP-206 cross fibers and molded leading and trailing "U" shaped members. This arrangement will allow maximum and uniform pressure transfer from the pressure bag to the laminate. The semicured insert plugs in the hub transition zone moved outboard during the closing of the hub mold. Less porosity occurred in these areas due to the inserts; however, their displacement ruptured the inner ply forming the spar wall and caused considerable fiber distortion of the cross ply fibers. To prevent this slippage, the inserts will be ganged together.

<u>Spar 5</u>

A one-piece pressure bag was fabricated to replace the previous two-piece "Y" shaped pressure bags. In the hub area of the pressure bag, coil springs of .160 inch O.D. with 25 pounds tension pull per inch of expansion were used as the mandrel. These were attached to stainless steel mandrels forming the torsion areas of the spar. The bag was wrapped with the level wrap L.R.-40 and silastic rubber tape cured at 320°F. On completion of cure, the bag was spirally wrapped with two plies of .0005-inch by .50-inch wide Teflon film.

The aluminum hub was cleaned, etched, and primed with BR-1009-49 primer .0005-inch to .001-inch thick. Six plies, three pieces per side, of FM-1000 1½ inches by 2 inches were laid into the aluminum hub grooves and heat tacked in place.

The hub was then wrapped with five cross plies and four spanwise plies sandwiched between the cross plies, with a cross ply in contact with FM-1000 plies. This completed the hub buildup, and the assembly was positioned on the spar assembly fixture. The one-piece pressure bag was stretched over the hub assembly and positioned in the grooves of the hub. The outboard ends of the pressure bag were clamped to the end posts of the spar assembly fixture and loaded in tension to approximately 20 pounds.

Molded leading edge and trailing edge epoxy fiber glass reinforced strips were positioned on the spar edges in the torsion area of the spar. The exposed surfaces of the strips were primed with tack primer BR-1009-49. Unidirectional cross-ply strips were then heat tacked for the full length of the edge strips, forming the first spar ply in the torsion areas. The outer cross ply in contact with the pressure bag in the hub region was wrapped tightly over the pressure bag and heat tacked in place. This ply butted the torsion area cross plies.

The second spar ply, a through spanwise ply, was positioned on the buildup. The ply was located at the center of the aluminum hub and worked into place from the center out. Preformed unidirectional ganged plug inserts were positioned at the extreme ends of the hub directly over the spanwise ply.

The hub cross ply was wrapped tightly over the inserts and spanwise ply which were heat tacked in place. Through spanwise plies three through eight were positioned on the buildup in order. The number of cross plies in the hub transition areas was cut to half of the previous number. The ninth ply was a cross ply which extended from one end of the spar to the other. The ply overlapped itself by approximately $\frac{1}{2}$-inch. The tenth through fourteenth plies were spanwise and were positioned on the spar assembly following the same procedure as with the preceding plies. As the spanwise plies were positioned in the mold and the torsion sections of the mold were fully closed, maintaining a 20-pound tension load on the ply ends. The mold assembly with the tension device was preheated in an oven to 180°F for 30 minutes. On completion of the preheat cycle, the mold assembly was removed from the oven and the hub section of the mold was closed. The upper hub plate was forced down on the buildup until it was flush against the stops; it was bolted in that position. The side plates were positioned with C-clamps and bolted in place. The mold assembly was again preheated

to 180°F for another 30 minutes. At the completion of this cycle, the mold was removed from the oven and the tension devices at the spar ends were tightened by applying a 100-pound total load to the spanwise plies. The spar remained in traction until it cooled to room temperature. The buildup extending beyond the mold was cut off, and air fittings were connected to the pressure bag. The pressure bag was pressurized to 80 psi, and the laminate was cured for 1 hour at 330°F $\pm$10°F in a forced draft air oven. On completion of cure, pressure was maintained until the laminate reached temperature.

The blade assembly was radiographically inspected after final cure.

Problems encountered in the lay-up of the spar buildup are listed below:

1. Considerable difficulty was encountered on positioning the one-piece pressure bag on the buildup. On spar fabrication, the usual gap developed between the outboard edges of the aluminum grip on the glass fiber laminate. A review of the problem resulted in removing the lay-up and pressure bag. The pressure bag was redesigned to include a 3/16-inch O.D. coil tension spring replacing the 3/16-inch steel cable hub mandrels. On positioning the pressure bag on the buildup, the coil spring allowed the bag to expand over the buildup and then recoil, retaining the laminate tightly in place against the aluminum hub. No gap occurred in this buildup.

2. At the completion of the preheat cycle, difficulty was encountered in closing the hub portion of the mold, particularly the hub side plates. Large C-clamps were used to force the plates into place. The closing pressure on the side plates was irregular and erratic, resulting in one of the plates lagging the other by a considerable amount. So much time was taken in closing the mold that the assembly had to be reheated to 180°F prior to applying a tensile load of 100 pounds to the ganged ends of the 12 through plies. Nonuniform loading of the through plies resulted with the ganged tension device.

Examination of the molded hub and torsion specimen revealed only one surface defect: a plastic chip embedded in the surface of the transition hub area on the leading edge of the spar.

Radiographic inspection of the completed specimen revealed the following:

1. The inner spar wall on the right-hand side only in the hub and transition region had an irregular cross section which was not parallel to the spanwise axis.

2. Light-density areas appearing as spanwise ribbons .060-.080-inch wide occurred in the hub region from station +2.5 to -2.5.

3. A metal chip was observed at the point of tangency of the torsion area to the hub transition.

4. The inner spar wall was uniform and parallel to the spanwise axis for the full length of the left-hand torsion area and the outer half of the right-hand torsion area.

Dissecting the specimen on completion of the static test of the specimen revealed the following:

1. The hub transition area (station 2.5 to 6.5 on both spars) was free of porosity.

2. The wall thickness was uniform throughout the hub transition area and the majority of the torsion areas.

3. The glass fiber insert plugs had moved outboard and distorted the preformed torsion area hub plies. The transition zone inner spar wall had rotated approximately 20° on its spanwise axis from its original horizontal position.

The expandable one-piece pressure bag had performed well, eliminating the hub buildup retention problem that occurred with previous fabricated spars.

The tension device eliminated the voids that occurred in the hub transition region in the previous spar. Difficulty was encountered, however, in applying uniform tension to the ganged spanwise through plies. Slippage of the plies occurred in the grip of the tension device; a redesign of the

device is mandatory. The new fixture will have individual retaining pins for all of the through spanwise plies. Loading of the plies will be accomplished by torquing each of the retention pins to 50 inch-pounds using a preset torque wrench.

Investigation of the plastic chips embedded in the spar laminate at the hub transition area leading edge indicated that they were pieces of epoxy filler material used to blend the hub transition zone of the hub mold. The epoxy filler will be replaced with an aluminum weld.

Spar 6

Pre-preg material XP-206 was changed to 1008S material. The one-piece pressure bag was utilized to fabricate all of the remaining spars in place of the "Y" shaped pressure bags.

The aluminum hub was cleaned, etched, and primed with BR-1009-49 primer .0005-inch to .001-inch thick. Six plies, three pieces per side, of FM-1000 $1\frac{1}{2}$ inch by 2 inches were laid into the aluminum hub grooves and heat tacked in place. BR-1009-49 tack primer was used to attach the FM-1000 plies to the hub. The hub was then wrapped with five cross plies and four spanwise plies of pre-preg, sandwiched between the cross plies with a cross ply in contact with FM-1000. This completed the hub buildup.

The one-piece pressure bag was stretched over the hub assembly and positioned in the grooves of the hub. The outboard ends of the pressure bag were clamped to the end posts of the spar assembly fixture and loaded in tension to approximately 20 pounds.

Precured reinforced "U" shaped strips were positioned on the spar edges of the torsion area. The exposed surfaces of the strips were primed with tack primer BR-1009-49. Pre-preg cross-ply strips were then heat tacked to the "U" shaped edge strips for the full length, forming the first spar ply in the torsion areas. The outer hub cross ply in contact with the pressure bag was wrapped tightly over the pressure bag and heat tacked in place. This ply butted the torsion area cross plies.

The second spar ply, a through spanwise ply, was positioned on the buildup. The ply was located at the center of the aluminum hub and worked into place from the center out. Preformed unidirectional ganged plug inserts were positioned at the extreme ends of the hub directly over the spanwise ply.

The second hub cross ply was wrapped tightly over the plug inserts and spanwise ply and heat tacked in place. Through spanwise plies three through eight were positioned on the buildup. The ninth ply was a cross ply which extended from one end of the spar to the other. The ply overlapped itself by approximately ½ inch. The tenth to fourteenth plies were spanwise plies which were positioned on the spar assembly following the same procedure as with the preceding plies. As the spanwise plies were positioned on the buildup, the ends of the spanwise plies were clamped to individual retention pins of the tension device and a small tensile load was applied during and on completion of the buildup. The finished assembly was positioned in the mold, maintaining a 20-pound tension load on the ply ends, and was preheated in an oven to 180°F. On completion of the preheat cycle, the mold assembly was removed from the oven and the hub section of the mold was closed and bolted. The side plates were forced closed with C-clamps and bolted in place. The mold assembly was again preheated to 180°F for 30 minutes. At the completion of this cycle, the assembly was removed from the oven and the spanwise plies were loaded in tension using a tension device consisting of 24 pins per end. Each of the tension pins retaining one end of the spanwise plies was torqued to 50 inch-pounds and locked in place, maintaining the load on the ply. All of the spanwise pins were torqued starting from the inner ply and working out. The spar remained in traction until it cooled to room temperature. The buildup extending beyond the mold was cut off, and air fittings were connected to the pressure bag. The pressure bag was pressurized to 80 psi, and the laminate was cured for 1 hour at 330°F in a forced draft air oven. On completion of cure, pressure was maintained until the laminate reached room temperature.

The blade assembly was radiographically inspected after final cure.

The spar was filament wound from station 2.25 to station 6.375 with eight wraps of Owens Corning SCG 150½ 3.83 HTS 901 fiber glass yarn. A tensile load of 6 to 8 ounces was maintained on the glass filament during winding. The blade was wound in an engine lath using the tool post to attach the filament winding device. The blade was rotated at 137 with a feed of 60 threads per inch. Upon completion of the winding of each layer, the filaments were coated with an epoxy laminating resin. The laminating resin system is as follows:

Epon 820	-	100 parts by weight
Versamid 125	-	10 parts by weight
DTA	-	6 parts by weight
Carbon Black	-	3 parts by weight

On finishing the winding of the eight wraps, all excess resin was removed from the buildup and the structure was oven cured for 3 hours at $165^{\circ}F \pm 10^{\circ}F$.

Problems encountered in the lay-up of the spar buildup are listed below:

1. 1008S was substituted for XP-206 unidirectional glass fiber epoxy pre-preg. The initial buildup tack of 1008S was excellent; however, positioned plies had a tendency to loosen and slip from one another.

2. Mechanical closing clamps built into the mold to provide uniform loading on the side plates during setting of the laminate were not satisfactory. The mechanical clamps sheared off when an attempt was made to close the side plates of the hub mold after the preheat cycle.

Several large voids developed during cure in the hub region at station 0. The specimen was severely indented in the hub transition region on the right-hand side.

The brass shim stock used to blend the flash marks between the torsion area and transition zone imbedded its edges into the laminate on both sides of the spar.

The transition from unidirectional pre-preg XP-206 to 1008S was accomplished without undue difficulty. A tack problem occurred with the 1008S material; the positioned plies loosened and slipped from one another. This was overcome by heat tacking the plies to the buildup and to each other with an electrical heat sealing iron.

This specimen was fatigue tested for flatwise and edgewise bending. The specimen failed in the hub transition zone. Failure occurred at a necked-down wall area, at the point of tangency with the torsion section on the leading edge of the spar.

The defect in the hub transition wall was caused by one end of the hub side plate mold being set too deep in the mold. Stops will be adapted to the side plates to prevent this on

future spars. Radiographic examination revealed the flaw in the inner spar wall. A comparison of X-rays of the fatigue tested spar to the original, prior to failure, pinpointed the origin of failure to the flaw in the inner wall. Radiographic examination also detected that the inner spar wall in the transition zones had an irregular cross section which was not symmetrical to the spanwise spar axis. This was verified on destructive examination.

The mechanical thumb screw clamps attached to the spar mold for closing the hub side plates will be replaced with a hydraulic hub press for the following reasons:

1. Uniform pressure can not be applied simultaneously to the hub mold side plates with the clamps.

2. Loads being applied by the mechanical system are not adequate to completely close the side plate.

3. There are no accurate means of measuring load being applied to the hub side plates during this forming operation.

The large voids in the leading and trailing edges which occurred in the hub section of the spar were caused by tensioning the spanwise plies, compressing and pulling them away from the outer wall of the hub mold. Additional hub fillers plies will be used on subsequent spars.

<u>Spar 7</u>

Buildup procedure was similar to spar 6 with the following exceptions:

1. The ganged plug inserts were molded in a ganged mold and were approximately one-third larger in volume than the previous inserts.

2. The hub portion of the mold was realigned and the bolt holes were rebushed. The hub side plates in the transition zone were filled with aluminum weld, contoured, and blended to match torsion spar areas.

3. A hydraulic press was fabricated so that hydraulic pressure of approximately 5000 pounds could be applied to the hub side plates to close the mold on the completion of the preheat cycle. The hub press at this time did not have the upper hydraulic cylinder. The blade was radiographically inspected on completion of cure.

No problems were encountered during spar lay-up. Difficulty was encountered on closing the mold after the preheat cycle. On applying uniform pressure to the side hub mold plates with the new hydraulic press, the upper mold plate lifted after buckling the four corner steel bolts retaining it against the side plates. The pressure was released, the side plates were withdrawn from the mold, and again the spar assembly was preheated. On completion of the preheat cycle, the upper plate was clamped to the lower portion of the mold, and hydraulic pressure was reapplied. The hydraulic pressure gages indicated that 8000 pounds was applied to the hub side plates to close them. The hydraulic load on the side plates produced a gap of .060 inch to .090 inch between the upper mold plate and the side plates at station 0. This gap could not be eliminated.

Examination of the cured spar revealed a few small voids in the hub section of the spar at station 0. The voids were up to .015 inch in diameter with no appreciable depth and were clustered together in a .375-inch diameter area on both sides of the spar. A mismatch of .015 inch occurred between the hub transition and torsion areas.

Radiographical examination of the spar specimen revealed the following:

1. Uniform wall thickness was found throughout the spar, with the inner wall parallel to the outer spar wall. No break in the inner spar wall and no necked-in regions were detected.

2. Light-density ribbon areas .015 inch to .030 inch thick occurred in the hub region from station 2.5 to -2.5 approximately 1/8 inch in from the outer edge of the spar wall and parallel to the outer wall. The light-density areas occurred on both sides of the spar hub. On destructive examination, no resin concentration could be detected.

Spar 8

Buildup procedure was similar to that for spar 7 with the following exception:

The hydraulic press was modified to include an additional hydraulic cylinder to apply vertical load to the upper hub mold plate to facilitate closing of the mold on completion of the preheat cycle. An overall view of the hub forming and spar tensioning fixture is shown in Figure 3.

Spar lay-up proceeded as planned with no difficulties. Problems were encountered in closing the hub portion of the mold using the revised hydraulic press.

Positioning and aligning of the hydraulic press went according to plan. However, the hub side plates could not be completely closed on applying a load of 8000 pounds. A gap between the side plate stops and the mold base was approximately .125 inch wide. The upper plate was not completely closed; a gap of approximately .060 inch occurred between it and the side plates.

On the second preheat, the temperature was increased to 200°F from 180°F and the assembly was held at temperature for ½ hour. On completion of the preheat cycle, the hub section of the mold was again closed, with the dial gages indicating 8000 pounds on the side and top hub mold plates. A .060-inch gap remained between the side plates and the mold base, and a .040-inch gap remained between the side plates and upper plate.

The preheat temperature was increased to 230°F from 200°F, and the spar and mold assembly was again preheated for ½ hour at temperature. On completion of the third preheat cycle, the hub section of the mold was reset. Pressure applied, as indicated by the dial gages, was 8000 pounds on the side and top hub mold plates. The side plates were completely closed, but a .030-inch gap remained between the upper mold plate and side plates at station 0. Some resin flowed from the hub bleed-out holes. The spar was cured with the .030-inch gap remaining between the upper and side mold plates. Inspection of hub thickness upon completion of the cure revealed that the hub was .030 to .040 inch oversize.

Spar 9

Buildup procedures were similar to those for spar 8 except for the following:

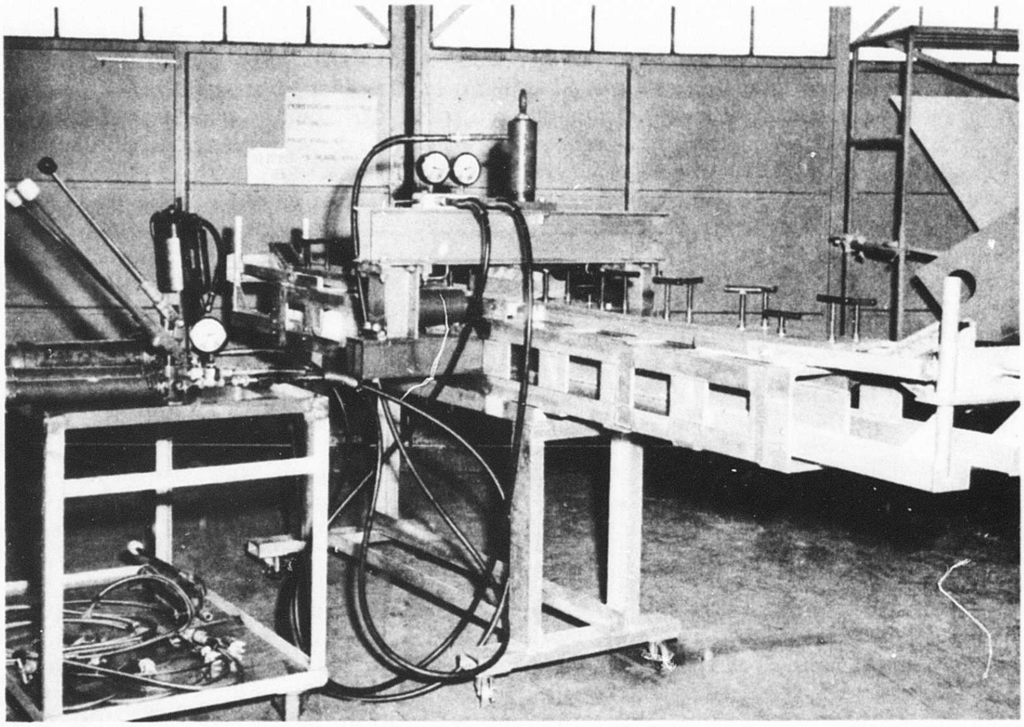


Figure 3. Spar Tensioning and Hub Forming Using Hydraulic Pressure, on Completion of Preheat Cycle.

1. The ganged insert plugs in the hub transition buildup were eliminated. Additional filler plies were centered on the hub buildup leading and trailing edges at station 0.

2. Buildup and mold assembly was preheated to $210^{o}F \pm 5^{o}F$ to facilitate closing of the mold.

Fabrication and cure of the specimen proceeded without incident. Lab technicians fabricated the specimen using established procedures with a minimum of engineering supervision.

The hydraulic press performed as anticipated without difficulty, completely closing the hub side and top mold plates.

Radiographic inspection taken of the finished molded spar specimens revealed continuous spar walls of uniform thickness without internal flaws.

The spar was dissected and examined for internal defects. The torsion areas and outboard spar section had no internal defects. The hub and transition areas had an irregular internal spar wall with variation in wall thickness and concentricity with the spanwise axis.

The press had been modified and strengthened prior to forming spar 9. The processing and forming of the spar proceeded without incident.

With the hydraulic hub press completed, the forming pressure, preheat temperature and time, and hub buildup could now be fully evaluated and changed as necessary.

Evaluation of the spar configuration on spars 7, 8, and 9, through radiographic inspection and destructive evaluation, revealed that the ganged plug insert used in the hub transition zones of spar 8 were moving during the forming operation, twisting and distorting the inner spar wall. On all subsequent buildups, the ganged plug will be replaced with filler plies sandwiched between the spanwise plies in the hub transition zones of the spar.

The voids occurring in the leading and trailing edges of the spar at station 0 were caused by two variables: trapped air and tensioning the spanwise plies. Air bleed holes were installed in the hub mold side plates, and filler plies were added in the center hub region leading and trailing edges. These changes were incorporated in spars 8 and 9, eliminating the voids.

Spars 10 and 11

Prior to fabrication of the full-length spar, the following additions and revisions were made to spar tooling:

1. Fabrication of full-length spar mold.

2. Rebuilding of hub mold.

3. Assembling of spar mold, tension device, and hydraulic hub press to a mold bed.

The aluminum hub was cleaned, etched, and primed with BR-1009-49 primer .0005 inch to .001 inch thick. One ply of FM-1000 2 inches by 7 3/4 inches was laid into the aluminum hub grooves on each side and heat tacked in place. BR-1009-49 primer was used to tack the FM-1000 ply to the aluminum hub. Five cross plies and four spanwise plies comprised the hub buildup, with the spanwise plies separating the cross plies from one another. A cross ply was the initial ply of the build-up which was in contact with the FM-1000 hub ply.

The hub buildup was positioned on the mold assembly bed with the one-piece pressure bag stretched over the hub assembly and positioned in the grooves of the buildup. The outboard ends of the pressure bag were clamped to the end posts of the spar assembly fixture and loaded in tension to approximately 10 pounds.

The premolded "U" shaped edge strips were primed with BR-1009-49 tack primer prior to assembly on the buildup. The strips were positioned on the spar edges of the bag assembly and heat tacked in place. Unidirectional cross-ply strips were then heat tacked to the edge strips, forming the first spar ply in the torsion and outboard areas. The outer cross ply in the hub region adjoining the pressure bag was wrapped tightly over the bag and heat tacked in place. This ply butted with the spar cross ply.

The second ply, a through spanwise ply, was positioned on the buildup. The ply was located at the center of the aluminum hub and worked into place from the center to the outboard end of the spar. Filler hub plies 11 through 16 were centered in the leading and trailing edges of the hub buildup and worked into the laminate. The adjoining hub cross ply was wrapped tightly over the spanwise ply and heat tacked into position. The hub transition filler plies were located butting the aluminum hub on both ends of the upper

and lower surfaces and were heat tacked in place. The through spanwise plies three through eight and the hub transition filler plies were positioned on the buildup. The ninth ply was a cross ply which extended the full length of the spar, with an overlapping joint of approximately $\frac{1}{2}$ inch. The tenth through fourteenth spanwise plies were positioned on the buildup along with the hub transition filler plies and cross plies following the same buildup procedure used with the preceding plies. As the spanwise plies were positioned on the buildup, the ends of the plies were clamped to the slot of the retention pin and a 2-pound load was applied to each of the plies.

The completed spar assembly was positioned in the mold. The hub portion of the mold was enclosed around the buildup but not locked up. The spar portions of the mold assembly were completely closed and bolted. The spar and mold assembly was placed in a circulating air oven and preheated to $200^{\circ}F \pm 10^{\circ}F$ for 30 minutes. On the completion of the preheat cycle, the assembly was removed from the oven, the hydraulic hub press was positioned on the mold bed, the hub portion of the mold was closed and locked, and the spanwise plies were torque loaded to 100 inch-pounds within a 30-minute period. The hydraulic press was used to apply enough force to close the upper and side hub mold plates. The upper hub plate was closed prior to closing the side plates, which were closed together at the same rate and equal pressure. The spar remained under tension loading until it cooled to room temperature. The buildup extending beyond the mold was cut off, and air fittings were connected to the pressure bag. The pressure bag was energized to 80 psi, and the laminate was cured for 1 hour at $330^{\circ}F$ in a forced draft oven. On completion of cure, pressure was maintained until the laminate reached room temperature.

Fabrication of spars 10 and 11 was performed by a lab technician and a shop machinist under engineering supervision. The lay-up techniques for spar 11 were identical to those for spar 10, with all plies cut and sequenced in the same manner. Filler plies were cut using cutting templates.

The retention grip of the pressure bag was changed from forward of the tension device to aft of it for spar 11. Difficulty was again encountered in closing the upper hub plate and maintaining sufficient pressure to maintain its position during the setting of the side plates. On positioning the side plates with the hydraulic press, the pressure bag extruded outboard from the spar approximately 2 inches per end.

No other fabrication difficulties were encountered during the buildup of the spar.

Radiographic examination of the completed spar revealed that the internal pressure bag had been severed in the hub area. Irregularities in the thickness of the spar wall and lack of symmetry of the inner wall with the spanwise axis occurred in the hub transition zones. No other spar defects were detected. The elimination of the .002 inch thick brass shims from the leading and trailing edges of the spar during cure did not cause excessive flash lines on the leading and trailing edges of the spar.

Spanwise creases occurred in the transition zone at station 6 on the top surfaces of the leading and trailing spar edges on both sides.

Debugging the tooling prior to and during the fabrication of spar 10 was the major effort in the lay-up of this spar. No fabrication problems were encountered in the buildup of the full-length spar; however, fabrication time was 16 hours as compared to 12 hours for the short torsion and hub spar specimen. Mechanically attaching the outboard ends of the pressure bag mandrels to the tensioning devices prevented sagging of the spar which had occurred during fabrication of earlier samples.

On forming the hub of the spar at the completion of the preheat cycle, the lower I-beam of the hydraulic hub press buckled, resulting in only partial closing of the hub mold. Tensile loading of the spanwise plies buckled the vertical support retaining the tensioning device. The hub press will be modified by replacing the aluminum I-beam with a rectangular steel extrusion with a $\frac{1}{4}$-inch wall, and the tensioning rack supports will be further reinforced.

The highly polished mold with a light coat of mold release was not adequate, resulting in the adhesion of the laminate to the mold surfaces in some areas.

Spar defects detected were the oversized hub caused by the incomplete cl ing of the spar hub mold, the delamination of the outer spanwise plies caused by adhesion of the spar laminate to the mold, and the mismatch of the spar hub transition area to the torsion areas of the spar. More blending of the transition area of the hub mold to spar torsion areas is required. Brass shims used to prevent excessive flashing of the fiber glass material at the mold parting line on the leading and trailing spar edges became embedded in the

laminate, cutting some of the spanwise plies in the hub transition zone. These shims will be eliminated on future spar buildup.

Spar 12

Buildup for spar 12 was similar to that for spar 10 with the following exceptions:

1. The number of hub transition plies was reduced from 16 to 12, and the plies were relocated.

2. The torque load on spar 12 was increased from 100 inch-pounds to 150 inch-pounds.

Fabrication of the spar was again performed by a lab technician and a shop machinist under engineering supervision using established procedures. All spar plies consisted of precut strips and template cut filler plies of 1008S unidirectional fiber glass epoxy pre-preg.

To eliminate the extrusion of the pressure bag from the spar ends, the tensile strength was increased. Fabrication of the spar proceeded without incident.

During the preheat cycle, the ambient oven temperature exceeded 320°F; in all previous preheat cycles, ambient temperature was maintained between 200°-220°F. This high preheat partially set the spar laminate and completely set up the exposed spanwise plies in the tensioning racks. On closing the hub portion of the mold, the pressure bag extruded from the outboard ends of the mold approximately 2 inches per end. The majority of the spanwise plies ruptured when the spanwise ply tensioning load was applied.

Radiographic examination of the completed spar revealed that the pressure bag had severed in the hub area. Distorted spanwise plies and a rippled inner spar wall occurred in the torsion area on both sides of the blade. Irregularities in the thickness of the spar wall and symmetry with the spanwise axis occurred in the hub transition zones.

External defects were spanwise identations in the spar laminate occurring at the outboard ends of the spar. Considerable surface roughness and porosity occurred at the outboard ends of the spar laminate.

Spar 13

Spar 13 was fabricated by the previous trained workers who fabricated spars 11 and 12. Spar 13 was fabricated without engineering supervision.

The pressure bag was again revised by increasing the ultimate tensile strength to 400 pounds from 150 pounds.

Fabrication of the spar proceeded without incident.

Upon closing of the hub portion of the mold, a hydraulic leak developed in the vertical hydraulic cylinder, resulting in only partial pressure being applied to the upper mold plate. The pressure bag extruded from the outboard ends of the mold approximately 2 inches per end. No other problems were encountered in the fabrication of this spar.

Radiographic examination of the completed spar showed that the pressure bag severed at two locations (station 2 at both ends of the hub). The inner spar wall was irregular, with considerable variation in thickness in the hub and transition areas only. Displacement and mislocation of the inner cross ply and spanwise ply occurred in the transition areas at both hub ends.

Visual inspection of the spar revealed no external defects.

Severance of the pressure bag in the spar hub region, extrusion of the bag from the outboard ends of the spar, and the placement and number of hub filler plies were the major processing problems encountered. Lay-up of these spars proceeded without incident.

On the completion of spar fabrication, spar cure, visual and radiographical inspection, and destructive analysis of spars 11 and 12, it was concluded that the hub buildup was too massive and that the numbers of hub filler plies would have to be reduced. One set (4 plies) of the filler plies was eliminated from the buildup of spar 12. Subsequently, on the evaluation of spar 12, the hub buildup was again reduced, eliminating 4 plies on spar 13. It was felt that the tendency for rupturing of the bag would also be reduced with a smaller hub buildup. The factors involved in the forming of the spar hub are as follows:

1. Spar hub lay-up during forming is compressed to approximately two-thirds of the original lay-up size.

2. At 200°F preheat temperature, epoxy resin in the spar laminate is a semiliquid.

3. The forces applied to the upper and side mold plates compressing the buildup apply approximately 740 psi to the laminate during the forming process.

4. On forming, the hub laminate buildup is compressed in two directions (top and bottom, trailing and leading edge surfaces), and the excess laminate is forced outboard in a spanwise direction. It was concluded that the spanwise displacement of the pressure bag of approximately 2 inches per end that occurred on spars 11, 12, and 13 was caused by considerable spanwise pressure applied to the bag during hub forming. This was verified when the tensile strength of the center hub area of the pressure bag was increased from 26 pounds to 150 pounds to 400 pounds respectively. However, in all cases, the bag extruded from both ends of the spar.

The problems of severance and extrusion of the pressure bag had occurred only on the above three spars, and a review of procedure and tooling prior to their manufacture revealed that the location of the outboard mandrel retention strap had been changed from inboard of the tensioning device to aft of it. Examination of the relationship of the strap to the pressure bag on spar specimens up to number 11 indicated that the strap bottomed out against the inboard end of the tensioning device and prevented the bag from moving outboard when under spanwise pressure during hub forming. Moving the strap aft of the tension device as was done on the above three spars allowed the pressure bag to move outboard at will.

The pressure bag on spar 14 will be revised to include 1/16-inch-diameter flexible steel cables silver-soldered to the steel mandrel. The outboard retention straps will be located ahead of and butting against the tensioning devices. The strap will be riveted to the pressure bag mandrels, assuring positive location of the straps to the bag and tensioning device.

During the preheat cycle on spar 12, the preheat temperature inadvertently reached 320°F. This temperature, although of short duration, caused partial cure on the spar laminate and completely cured the exposed spanwise plies in the tension

racks, resulting in only partial tension loading of the spanwise spar plies. The overrun of the ambient oven temperature during preheat verified the need of tensioning and the effect of excessive preheat. Without tension load applied to the spanwise plies, the crimped and distorted glass filaments were not straightened in the spar torsion area adjoining the hub transition zone. The distorted fibers were detected on radiographic examination of the spar and verified on destructive spar evaluation, again proving the merit of radiographic inspection as an important tool for nondestructive inspection and control of spar quality.

Spar 14

This was the final full-length spar and became the main structural element of the whirl test article. The aluminum hub was cleaned, etched, and primed with BR-1009-49 primer, .0005 inch to .001 inch thick. One ply of FM-1000, 2 inches by 7-3/4 inches, was laid into the aluminum hub grooves on each side and heat tacked in place. BR-1009-49 primer was used to tack the FM-1000 ply to the aluminum hub. Five cross plies and four spanwise plies comprised the hub buildup, with spanwise plies separating the cross plies from one another. The initial hub ply, in contact with the FM-1000, was a cross ply. The assembly was positioned on the hub support of spar fabrication assembly mold and positioned in the grooves of the buildup. The outboard ends of the pressure bag were clamped to the tension racks, which exerted approximately 10 pounds tensile load to the bag.

The premolded leading and trailing edge spar strips were primed with BR-1009-49 tack primer prior to assembly on the pressure bag. The "U" shaped strips were positioned on the edge of the bag assembly and heat tacked in place. Unidirectional cross-ply strips were heat tacked to the edge strips, forming the first spar ply in the torsion and outboard areas. The outer cross ply (hub region) in contact with the pressure bag was wrapped tightly over the pressure bag and heat tacked in place. This ply butted with the spar cross plies.

The second ply, a through spanwise ply, was positioned on the buildup. The ply was located at the center of the aluminum hub and worked into place from the center to the outboard end of the spar. Filler hub plies ten through fourteen were centered within the aluminum hub groove and worked into the hub laminate on both edges. The hub plies were wrapped tightly over the spanwise plies and heat tacked into position.

The hub transition filler plies were located in the hub buildup and heat tacked in place. The next through spanwise ply was slit spanwise at the midpoint of the ply for approximately 8 inches. The ply was opened at the slit, positioned around the edges of the aluminum hub, and worked into place from the center to the outboard ends of the spar. Butt line for the even-numbered plies occurred on the top and bottom spar surfaces; for the odd-numbered plies, on the leading and trailing edges of the spar. Plies were butted to one another with .100 inch overlap allowed. The remaining spanwise plies (four through eight) and hub transition filler plies were positioned on the buildup in order. The ninth ply was a cross ply which extended the full length of the spar and overlapped itself by approximately .500 inch. The tenth through fourteenth plies were spanwise and were positioned on the buildup along with the hub transition filler plies and cross plies according to the cutting order, following the same buildup procedure used with the preceding plies. As the spanwise plies were positioned on the buildup, the ends of the plies were positioned in the slots of their retention pins. The slack was removed from the ply, but no tension load was applied.

On the completion of the assembly, the spar was positioned in the mold. The hub portion of the mold was assembled around the buildup but was not completely closed. The spar section of the mold was assembled around the spar and closed and locked. At this point the spar and mold assembly was placed in a circulating air oven and preheated to $200^{\circ}F \pm 10^{\circ}F$ for 30 minutes. On the completion of the preheat cycle, the assembly was removed from the oven, the hydraulic hub press was positioned on the mold bed directly over the hub, and hydraulic pressure was applied to hub mold, closing it. A 10,000-pound load was applied to the upper hub mold plate, thus closing the upper plate prior to positioning the side plates. The side plates were closed together at the same rate and equal pressure of 8000 pounds. The mold was bolted closed while maintaining hydraulic load. The spanwise plies were torque loaded to 150 inch-pounds. The through spanwise plies were tension loaded starting with the inner plies and working out, torquing the ends of the given ply simultaneously. The spar remained under tension loading until it cooled to room temperature.

The spar buildup extending beyond the mold was cut off at the mold ends, and air fittings were connected to the pressure bag. The pressure bag was pressurized to 80 psi, and

the laminate was cured for 1 hour at $330^{o}F \pm 10^{o}F$ in a forced draft oven. On completion of cure, pressure was maintained until the laminate cooled to room temperature.

Fabrication of spar 14 was performed by the same personnel who fabricated spar 13 without direct engineering supervision.

The pressure bag was revised so that through flexible steel cables 1/16 inch in diameter were permanently attached to the stainless mandrel. Prior to spar fabrication, retention tabs were riveted to the pressure bag at both outboard ends adjoining the tension devices. The vertical hydraulic cylinder was rebuilt prior to use on this spar. Fabrication of the spar and closing of the hub portion of the mold proceeded without incident or problems. The bag did not extrude from the outboard ends of the spar on closing the hub portion of the spar mold.

Radiographic examination of the completed spar revealed that the internal pressure bag remained intact and positioned in the hub area of the spar. The spar walls throughout were uniform in thickness, and the inner wal was symmetrical with the outer wall in all areas. There was some distortion of the pressure bag in the transition zones of the hub which caused some minor irregularities.

On inspection, visual and radiographical, no flaws were detected with the exception of minor nodes on the inner spar wall, torsion area inboard, and right-hand side. These were caused by ripples in the pressure bag.

The pressure bag outboard retention straps adjoining the inboard edges of the tension devices prevented excessive spanwise movement of the bag during hub formation. The ripples in the pressure bag indicated that 1/8 inch to 1/4 inch spanwise outboard movement of the bag occurred in relationship to the stationary mandrels and spar. The examination of this spar indicated that a satisfactory method for spar fabrication had been devised and that a useful sample of good quality had been produced.

Airfoil Panel Fabrication

The airfoil panels are manufactured as completely cured and finished subassemblies which are subsequently bonded to the spar. Four such subassemblies are required to make a complete rotor, each representing either the top or the bottom of one blade. One panel consists of an outer skin and an inner facing, both of which are fiber glass and are bonded to a carved honeycomb core. The outer skin forms the external airfoil surface, while the inner facing is basically a flat sheet located on the airfoil chord plane. The inner facing contains one full-length depression which matches half of the spar elliptical contour. The skins are a number 120 glass fabric preimpregnated with Narmco 500 resin which cures at 250°F. The outer skin and the core are joined in a preliminary step using a layer of AF 126 Type I adhesive, which also cures at 250°F. The inner surface of the core is then carved to accept the local structural elements, and the inner facing is added using the same adhesive.

The remaining operations which complete the rotor are performed in a relatively straightforward manner. The basic rotor components prior to assembly are shown in Figure 4. In that figure the heavy ribs have been previously bonded to the spar, while the airfoil panels and elastomeric supports are ready for installation. This major assembly step is conducted at high temperature; however, the leading-edge cap, pitch horn, and tip cap are subsequently bonded with low temperature setting adhesive. The rotor is shown subsequent to major assembly bond in Figure 5 with diaphragm removed.

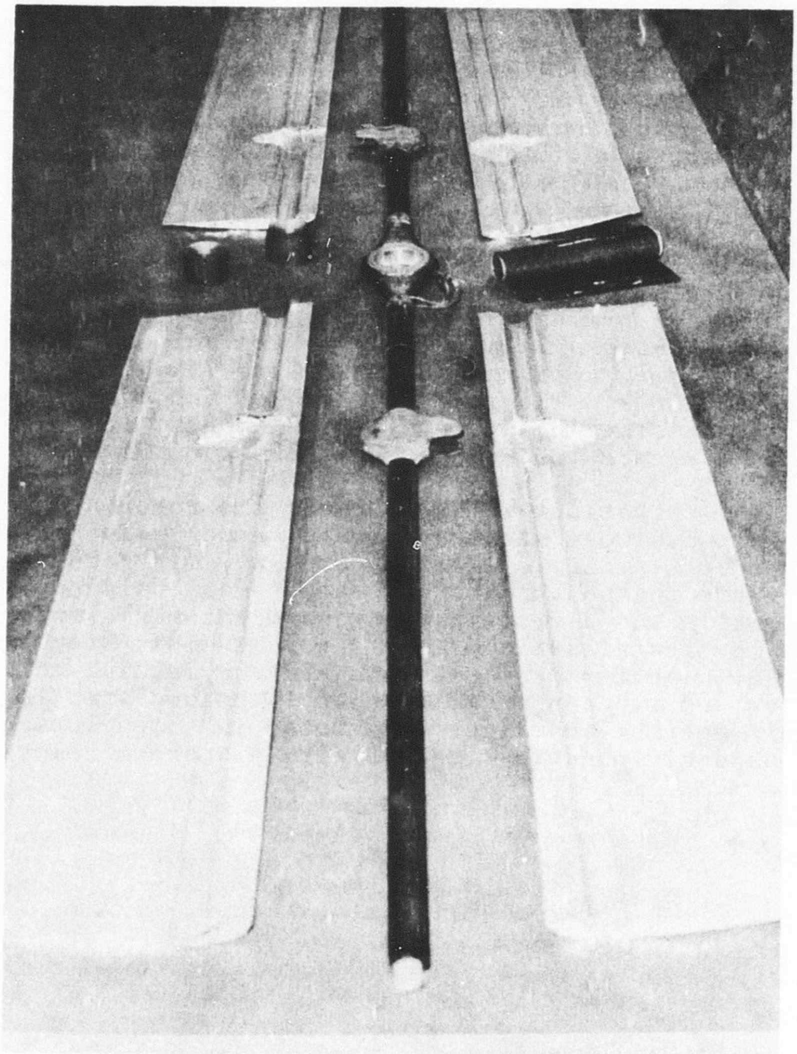


Figure 4. Fiber Glass Tail Rotor Components Prior to Assembly Bond.

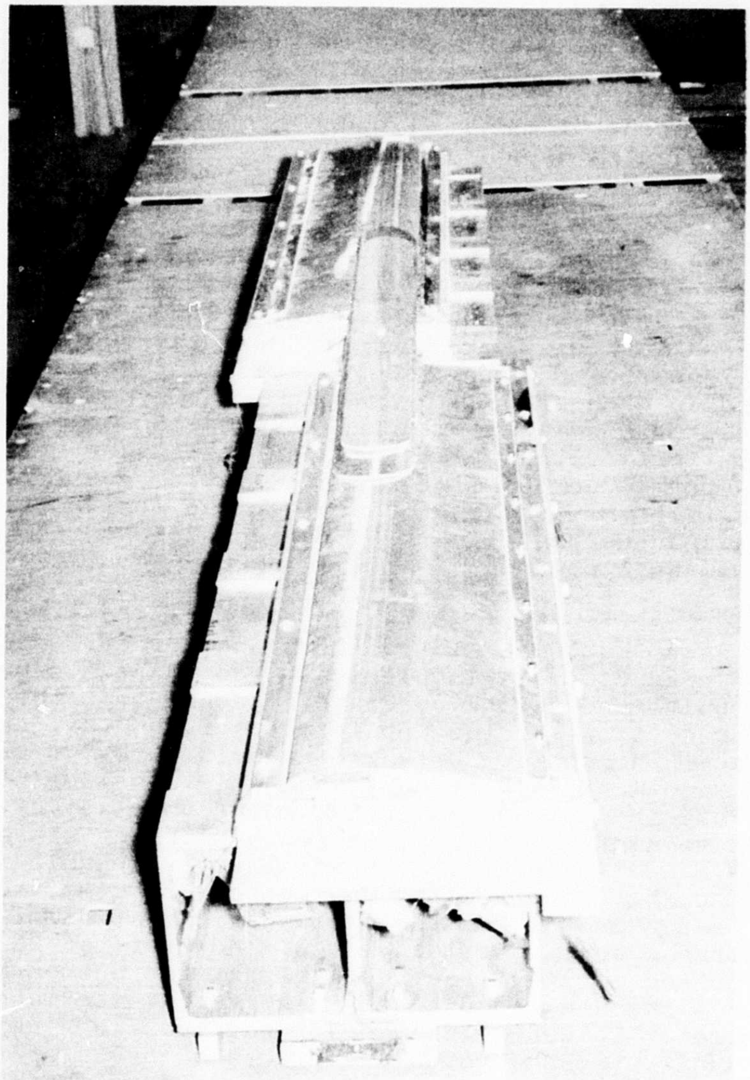


Figure 5. Rotor Assembly on Completion of Final Autoclave Cure with Diaphragm Removed.

TEST PROGRAM

A limited amount of testing was included in the present program for the purpose of evaluating the design as it evolved and providing an indication of the feasibility of this rotor concept. Testing of material coupons and small-scale laboratory samples is not reported here. The basic test program consisted of static and fatigue tests of spar assemblies and a whirl test of the complete rotor.

BENCH TESTS

The basic approach to the development of the spar fabrication process was to improve the methods, the tooling, and the techniques based upon troubles encountered and deficiencies found in each succeeding sample. The evaluation of each spar consisted of visual external examination, radiographic inspection for internal flaws, coupon testing of specimens cut from spars, and tests of the full-scale spar structure. The latter type of test is, of course, the most convincing, since it includes the effects of the complete design and fabrication development.

Table III presents the results for all full-scale spars tested. As noted, five static tests and three fatigue tests have been conducted. All full-scale testing was complicated by the requirement for an adequate attachment to the outboard spar section for the application of the full centrifugal force. The static tests produced failures at various levels. Specimen 2 achieved a reasonable level of strength; however, specimens 3, 4, and 5 failed at a relatively low level due to distorsion of the through plies of glass. Specimens 6 and 7 appeared by nondestructive examination to be of reasonably good quality and hence were committed to fatigue test. Spar 8 was the last static test sample, and it sustained the highest load level. However, at 26,000 pounds applied tension, the test grip at the outboard end of the spar failed and a substantial shock was experienced by the specimen. Sudden relaxation of the tensile strains would cause a stress wave to traverse the length of the specimen and induce extraneous stress patterns in the hub and transition areas. Upon subsequent repair and retest of specimen 8, failure of the hub area occurred when the 26,000 pound load level was again reached. It is probable that significant structural damage had been sustained in the hub region due to explosive unloading. This damage was not discernible by any of the nondestructive inspection means

TABLE III. SPAR TEST RESULTS - FIBER GLASS TAIL ROTOR

Spar Serial No.	Type of Test	Test Results	Remarks
2	Static tension	Failed at 23,200 lb. tension.	Failure resulted from spanwise cracks induced in prior static torsion test.
3	Static tension	Failed at 9,000 lb. tension.	Low failure caused by kinked fibers in hub transition region.
4	Static tension	Failed at 13,500 lb. tension.	Failure caused by distorted hub area fibers.
5	Static tension	Test stopped at 20,000 lb.; apparent yield at 18,000 lb.	Specimen had reduced fiber distortion but still failed earlier than expected.
6	Fatigue	Failed after 1.09 x 10 cycles at $\pm$8900 psi.	Failure influenced by locally thin spar wall at fracture location.
7	Fatigue	Test stopped after 5.0 x 10^6 cycles at $\pm$8900 psi.	No failure.
8	Static	Failed at 26,000 lb. tension.	In initial loading test, grip failed at 26,000 lb.; on subsequent loading, specimen failed at 26,000 lb. probably affected by shock unloading.
9	Fatigue	Test stopped after 5.0 x 10^6 cycles at $\pm$8900 psi.	No failure.

available; however, the subsequent test result seems to bear this out. Without this unfortunate experience, it is probable that the spar could have withstood considerably more load; however, since it had shown adequate strength, static testing was discontinued.

Fatigue testing of spars 6, 7, and 9 was conducted at levels which are expected to be representative of high-speed level-flight conditions. The centrifugal force tension was 43,000 psi, a 3-degree steady pitch angle was induced, and the specimen vibrated at 11.0 cps at a vibratory stress amplitude of $\pm$8900 psi. This vibratory stress amplitude was induced by a combination of edgewise and flatwise bending, with edgewise being more predominant, as is expected in operation. The first fatigue test specimen, serial number 6, failed after 1.09 million cycles of load application. Study of the fracture mode, shown in Figure 6, and location and correlation with radiographic negatives revealed that the failure was influenced by the presence of a locally thin wall and by resin starvation. This had been caused by the lack of positive stops on the hub mold side plates. The tooling was modified to correct for this deficiency, and the problem did not reappear on subsequent specimens. Spars 7 and 9 were tested under the same conditions and sustained 5.0 million cycles of load application without failure. These test points are illustrated in Figure 7, which is a typical semi-logarithmic stress-cycle plot of the data using a curve shape extracted from information published by the material manufacturer. This figure provides a basis for preliminary evaluation of the fatigue capability of the rotor, which is considered adequate for the purposes of the present program.

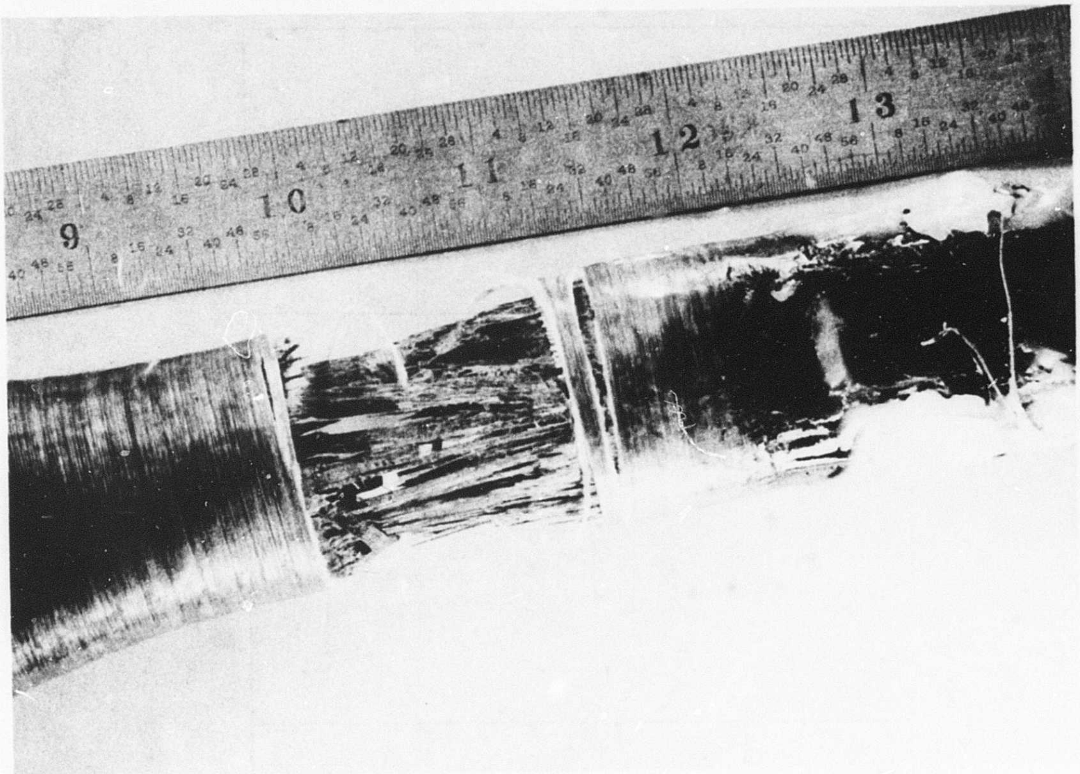


Figure 6. Fracture Produced in Fatigue Test of Spar 6.

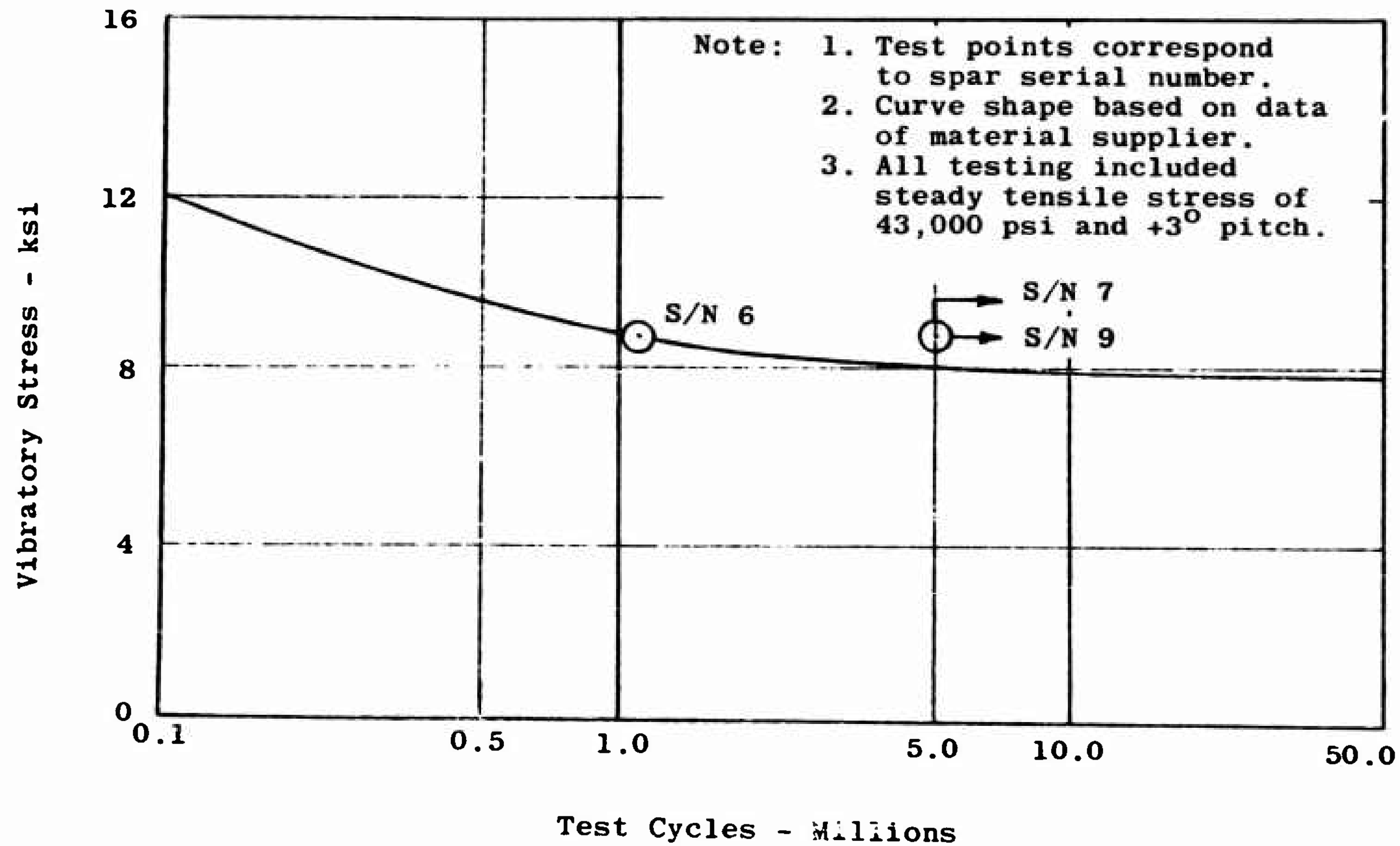


Figure 7. S-N Curve of Spar Vibratory Stress vs. Test Cycles.

WHIRL TEST

Spar 14 was selected for fabrication into a complete rotor for whirl test. Prior to installation of the rotor on the rig, the spar was instrumented with bending pairs of strain gages for both flatwise and edgewise bending at stations 7.96 and 9.71. Static natural frequencies of the rotor were determined by plucking the blade while the rotor was mounted to a rigid base. The fundamental frequency was found to be 12.5 cps edgewise and 6.1 cps flatwise for the nonrotating case. Similarly, the natural frequency of the whirl rig was determined by impact test for various simulated hub weights. At the actual hub weight including slip ring of 13.5 pounds the critical flywheel resonance frequency was calculated to be 2080 rpm using a conservative estimate of stiffness of the blade centering spring. Adequate margin above the 1732 rpm operating speed was thus obtained. Figure 8 shows an overall view of the rotor mounted on the whirl rig with instrumentation and slip ring assembly in place.

The natural frequency of the rotor in edgewise bending while rotating was predicted to coincide with rotational frequency at about 51 percent rotor speed. Analysis of strain gage data obtained during runup showed the existence of a resonance at 710 rpm or approximately 41 percent rotor speed. This resonance did not cause any problems throughout the whirl test program. Vibratory edgewise bending moments (1/rev.) obtained during runup are shown in Figure 9. Data were also recorded at 0, $\pm$3 and $\pm$6 degrees of blade pitch; however, no significant trends appeared. This result was expected for the hover case.

Following the collection and analysis of the above strain gage data, the rotor was subjected to a limited endurance whirl program. A total of 25 hours of operation at full rotor speed was accumulated in blocks of 1 hour with intermediate inspections. Successful completion of this phase of the program lends considerable credibility to the conviction that the concepts embodied in this unique rotor provide a practical new design approach and that they complement each other in such a way as to provide a significant advance in rotor technology.

At the completion of 25 hours of operation, no basic deficiency in the specimen could be detected which would in any way require revision or reevaluation of the concept. An incipient bond void did appear, however, at the aft edge of the leading edge ballast weight. This void occurred in a secondary low-temperature bond and could readily be repaired.

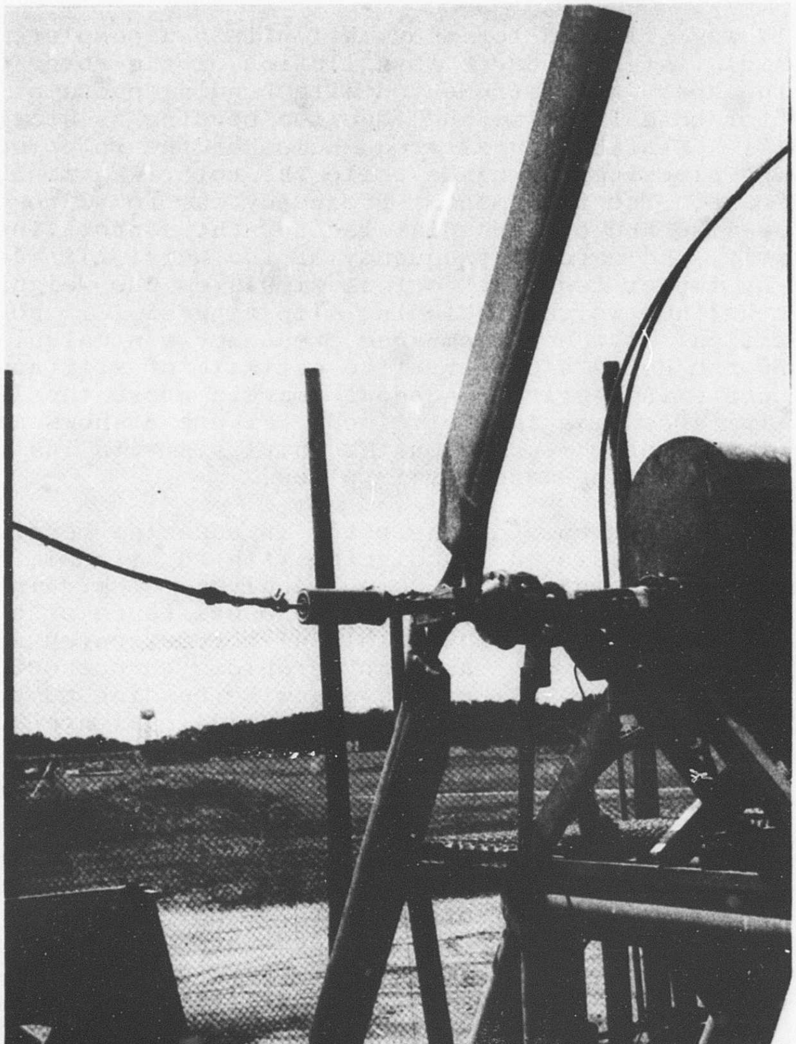


Figure 8. Fiber Glass Tail Rotor Mounted on Tail Rotor Whirl Test Rig.

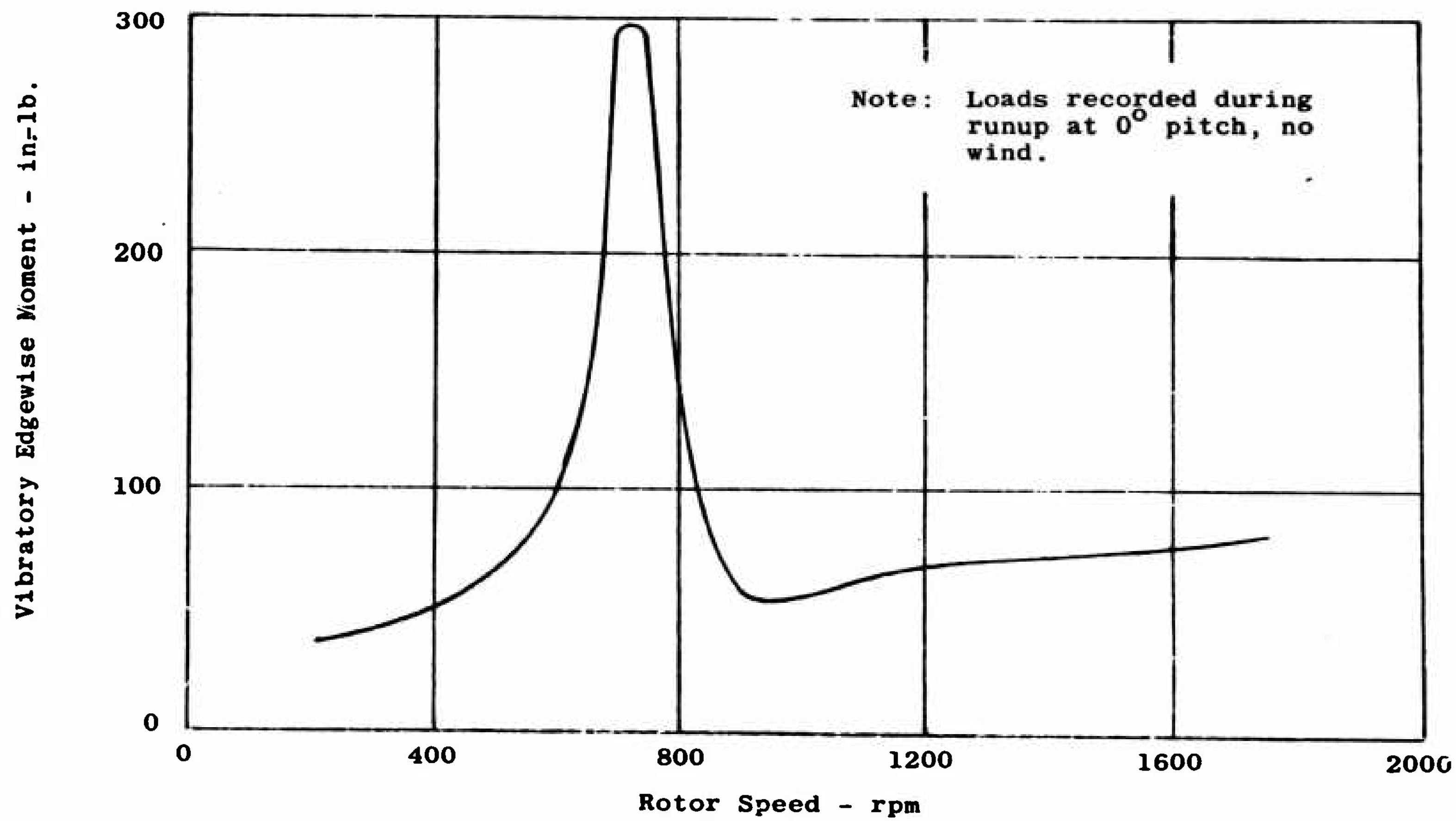


Figure 9. Vibratory Edgewise Moments Recorded During Rotor Runup.

With improved tooling and fabrication procedure for this area of the rotor, a high-temperature bond could be employed and the reliability of the weight attachment could be greatly enhanced. Additional whirl testing of this rotor is contemplated.

ESTIMATED PRODUCTION COST

The fiber glass tail rotor which is the subject of the development effort on this program is unique in many ways. The type of material, its application, the fabrication techniques employed, and the duty it must endure in the end product all contribute to the novelty and also the attraction that this rotor enjoys. The fabrication methods used to produce a limited quantity of rotors in this program could be put into production to manufacture a large quantity of rotors. This would require a considerable amount of hand labor and would therefore be unnecessarily costly. A reproducibility phase was included in the present program, and the results were indeed gratifying, considering the number and status of available tools. The results of this effort provided a clear appreciation of the importance of tooling, both in reproducibility and in reduced production cost. In those operations where tooling was used repeatedly on consecutive spars, the results were quite uniform and a continuous reduction of man-hours required was evident.

Extrapolation of this experience has led to the conclusion that the recurring cost of producing the rotor on a full set of production tooling would be less than $1,000. This cost would of course be affected by the degree of automation that could be achieved, as would the reproducibility of the rotor. In order that this subject be thoroughly explored, it is recommended that methods for automating the various steps in the production of this rotor be studied and that final production costs be projected based upon the results of this study.

CONCLUSIONS

It is concluded that:

1. A fiber glass tail rotor with a monolithic spar made of directed fibers can be fabricated under practical manufacturing conditions.

2. This rotor design provides the opportunity for a significant advance in rotor technology, particularly in the areas of cost and maintenance.

3. The basic feasibility of this rotor concept has been proven by the completion of limited bench testing and a 25-hour whirl test.

APPENDIX I

STRESS ANALYSIS

The critical area of the spar is station 5.5, the outer end of the transition from the hub to the basic pitch-spring section. A stress analysis of this section for the conditions of the whirl test follows:

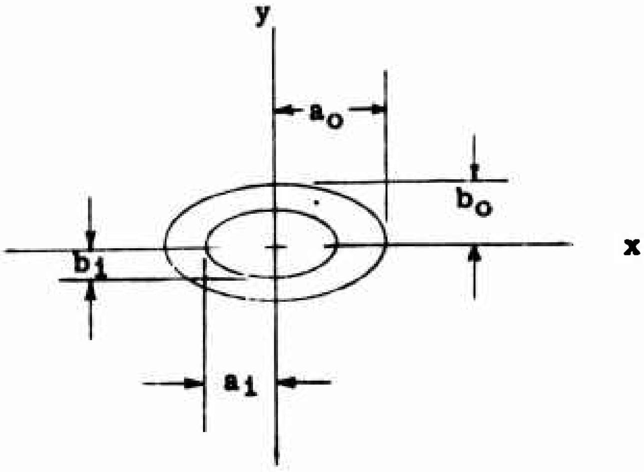
Section Properties

a_o = 0.625 in.
b_o = 0.313 in.
a_i = 0.365 in.
b_i = 0.143 in.

Area = 0.450 in.^{2}

I_{x-x} = .0142 in.^{4}

I_{y-y} = .0545 in.^{4}



Weight and Span Moment

Total rotor weight, less hub = 19.4 lb.

Weight per blade = 9.7 lb.

Span C.G. = 22.4 in.

Span moment = 217 in-lb.

Condition	Rotor Speed rpm	Centrifugal Force C.F. (lb)	CF/A (psi)
Min. power on and off	1454	12,950	28,800
Max. power on	1654	16,750	37,200
Limit power on and off	1732	18,400	40,900

Blade bending moments were calculated for the following steady-state condition:

Required thrust	650 lb.
Required pitch angle	10.4 deg.
Rotor speed	1730 prim

and the resulting moments were:

$$M_y = 1050 \text{ in-lb.}$$

$$M_x = 430 \text{ in-lb.}$$

Analysis has shown that the maximum spar stress occurs at a point on the external contour where x = .490 and y = .188 in. The combined stress at this point is therefore

$$f = \frac{C.F.}{A} + \frac{M_y X}{I_{y-y}} + \frac{M_x Y}{I_{x-x}}$$

$$= \frac{18400}{.450} + \frac{1050(.490)}{.0545} + \frac{430(.188)}{.0142}$$

$$= 56{,}070 \text{ psi}$$

This applied stress must be compared to an allowable stress for the material and design. Static testing to date has achieved a centrifugal force of only 26,000 pounds, at which time the specimen was damaged due to failure of a test grip. Small sample testing and the manufacturer's data provide an ultimate tensile allowable stress of 140,000 psi at typical resin content. The resulting margin of safety is therefore

$$M.S. = \frac{140{,}000}{1.5(56{,}070)} - 1 = \underline{\underline{+0.66}}$$

The actual margin available is probably somewhat less than this; however, the spar strength is undoubtedly adequate.

APPENDIX II

AEROELASTIC ANALYSIS

An aeroelastic analysis has been conducted to determine the suitability of the glass reinforced tail rotor blade for whirl testing. The analysis included the following: (1) calculation of blade out-of-plane and in-plane bending frequencies as well as torsional frequency; (2) rotor stability and blade airloads; (3) out-of-plane and in-plane bending moments and shears; and (4) proximity to the shaft critical condition and system resonances.

Blade physical properties were supplied in graphical form. The torsional, in-plane bending, and out-of-plane bending frequencies for the blade were obtained using existing computer programs. As this is a teetering rotor, both the cantilever and pin-ended configurations were considered for the out-of-plane motions to simulate the symmetric and antisymmetric modes. The first four modes were calculated for the in-plane and out-of-plane blade motions. Table IV lists the frequencies for the two ballast conditions divided by operating rpm. In computing the frequencies, the in-plane static stiffness was affected by the ballast rod, but the out-of-plane and torsional static stiffnesses were assumed to be unaffected.

As shown in Table IV, the first mode in-plane natural frequency is less than one cycle per revolution at full rotor speed. When the rotor is static (not rotating), this natural frequency is of course greater than rotational speed, and it follows that the natural frequency of the first in-plane bending mode must coincide with rotational speed at some point during runup. This point was in fact calculated to be 51 percent of full rotational speed. The anticipated damping from both aerodynamic and structural sources, particularly from the fiber glass material of the rotor itself, should be sufficient to prevent this resonance from becoming a problem, since it does not occur near an operational speed. Additional calculations have indicated that modest design changes could increase the natural frequency at full rotor speed to something greater than one-per-rev without impairing the basic rotor concept.

TABLE IV. BLADE NATURAL FREQUENCIES

Bending Frequency Per Revolution
Rotational Speed = 181.28 rad/sec.

	No Ballast			With Ballast		
Mode	I.P. Cant.	O.P. Cant.	O.P. Pin	I.P. Cant.	O.P. Cant.	O.P.PPin
1	.684	1.075	.999	.657	1.066	.999
2	8.057	2.605	2.331	9.778	2.587	2.362
3	19.003	5.088	4.246	24.287	4.924	4.289
4	36.632	7.798	7.025	42.738	7.595	6.743

TORSIONAL FREQUENCY (STATIC)

No Ballast		With Ballast	
Control Root	Blade Root	Control Root	Blade Root
96.04 cps	2.43 cps	85.9 cps	2.16 cps

Blade stability and loadings were calculated with an existing computer program that uses blade flapping and feathering as the available degrees of freedom. It was found that the unballasted blade was potentially unstable in pitch, with a very slow buildup in pitch oscillation following an arbitrary input. The blade with leading-edge ballast was stable in pitch, and both designs were stable in flapping. Blade bending moment distributions, both in-plane and out-of-plane, were calculated for a thrust of 679 pounds and rotational speed of 181 radians per second. At the critical root section, station 5.5, the in-plane moment is 1050 inch-pounds and the out-of-plane moment is 430 inch-pounds.

Due to the natural frequency characteristics of this rotor, it is necessary to assure freedom from the shaft critical condition. This was done using conventional theory of self-excited mechanical oscillations of hinged rotors. Rotor and whirl rig characteristics were used in the analysis which showed that shaft whirl would not occur up to 126% of rotor speed. Resonance characteristics of this particular blade and pylon combination showed that the two degrees of freedom would be encountered at 51% and 125%. Since neither resonance occurs close to the design operating speed of the rotor, continuous operation close to resonance will be avoided.

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13. ABSTRACT

An engineering program has been conducted for the purpose of investigating the feasibility of a new rotor concept utilizing a monolithic spar of directed glass fibers supported in an epoxy matrix. This concept makes use of the anisotropic property of the material to eliminate pitch bearings and thereby reduce maintenance requirements. The program included design, fabrication development, analysis and test phases. The latter two phases were of limited scope since the intent of the program was a basic feasibility investigation. The rotor has satisfactorily completed all phases including a 25-hour whirl test. It was concluded that rotors of this general configuration are practical, offer significant advantages, and can be fabricated in a production environment.

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